BEAM PHASE DETECTION FOR PROTON THERAPY ACCELERATORS

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Abstract

The industrial application of proton cyclotrons has become one of the important contributions of accelerator physics to medical therapy during the last years. Beam phase, energy, and intensity of the accelerated proton bunches can be detected by non-intercepting capacitive cylindrical probes. For the read out of the detected pulsed signals an advanced phase detection system using vector demodulating technique was developed. It has a very large dynamic range allow measurements over a beam current range of up to three orders of magnitude. In order to avoid interference from the fundamental cyclotron frequency of 72 MHz, the phase detection is performed at the second harmonic frequency. A phase detection range of 180° was achieved at the fundamental frequency. To improve accuracy a digital low pass filter with adjustable bandwidth and steepness is implemented. With an estimated sensitivity of the capacitive pickup in the beam line of 30 nV per nA proton beam at 250 MeV, accurate phase and intensity measurements are expected to be possible down to beam currents of 3.3 nA. First measurements at the cyclotrons will show how far the resolution will be limited to higher values by RF disturbance at the fundamental frequency.

INTRODUCTION

Two superconducting proton cyclotrons (250 MeV) for medical therapy are being commissioned by ACCEL Instruments for the Paul Scherrer Institute in Switzerland and the Rinecker Proton Therapy Center in Munich [1,2]. For both, a phase detection system was developed, which allows the measurement of beam phase, energy, and average beam current.

At defined positions in the beam line the phase relation of the proton bunches will be measured in comparison to a reference signal either from the master oscillator or a pick-up probe inside the cyclotron. In addition, the charge amount per bunch has to be determined. Because the bunches are injected in the beam line with a frequency of 72 MHz, it is possible to allocate an average beam current I_{mean}. The phase relation of the beam in the beam line can change because of the temperature drift of the large thermal mass of the cyclotron. In addition to active thermal stabilisation of the cyclotron the phase of the extracted beam is monitored by our phase-detecting (PHD) system to make a feedback correction system possible. Another important information is the actual beam current. The measurement of the phase shift between two positions in the beam line makes the determination of the actual proton energy possible. The proton energy can be adjusted by a degrader facility.

All three beam parameters will be derived from non-intercepting measurements of the beam bunches using cylindrical capacitive pickups. One of the three pickups is placed as the first beam line element behind the cyclotron and two further downstream in a straight section of the beam line to enable energy measurements.

PRINCIPLE OF MEASUREMENT

The proton beam is fed through the cylindrical capacitive phase probe which is externally grounded via a 50 Ohm resistor. As a result of the acceleration inside the cyclotron, the proton beam is concentrated within less than 20° phase space of the fundamental RF frequency of 72MHz. When these charge bunches enter or leave the cylinder of the pickup the induction of mirror charges lead to a rise or drop resp. of voltage over the 50 Ohm resistor. The connected phase detection read out electronic detects the induced differential voltage pulses with a high frequency of 72 MHz.

In principle, it is desirable to measure the phase of the charge bunches in relation to the fundamental frequency of 72 MHz. But because of the intense disturbing radiation both on the phase probe and the signal line the measurement is not performed at 72 MHz. The voltage pulses generated by the charge bunches can be seen as a Fourier sum of the fundamental frequency and all higher harmonics. As the pulse is short compared to the cycle duration T=1/72 MHz, the Fourier component at the second harmonic (144 MHz) has a similar amplitude as at the fundamental frequency. But the amplitude of RF disturbance at 144 MHz is expected to be more than 50 dB smaller compared to those at 72 MHz.

The second harmonic contributions of the pulses are first filtered and amplified several times, then mixed with a reference signal and finally converted into DC signals by an I/Q-demodulator. The resulting values I and Q describe the phase difference between the measured and the reference signal and the amplitude of the measured signal. I and Q can be seen as the real and imaginary part of a vector in the complex plane. The amplitude A corresponds to $\sqrt{(I^2+Q^2)}$, the phase difference $\delta\phi$ can be derived from $I = A*\cos(\delta\phi)$ und $Q = A*\sin(\delta\phi)$.

HARDWARE REALISATION

The whole phase-detecting system contains

- the phase probe (PHP),
- the preamplifier and the signal line,
- the data aquisition unit and the control computer (PHE),
- the control software.

Phase probe

The capacitive phase probe is a simple and robust beam diagnostic that is used to make non-intercepting

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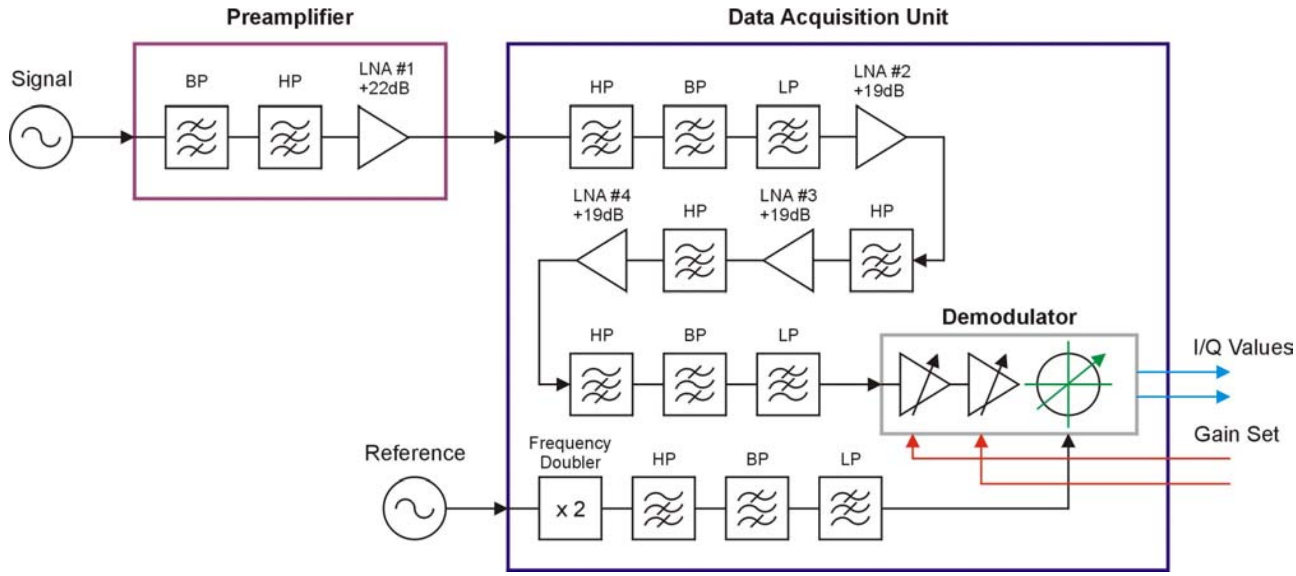

Figure 1: Block diagram of the phase detection system.

measurements. Phase, current and energy measurements can be made during patient treatments. The simple detector geometry consists of a 100 mm long cylindrical metal pickup that is mounted inside the beam line tube. The pickup cylinder is positioned with electrical isolators at the centre axis of the beam line tube and grounded externally over a 50 Ohm resistor. The expected signal from the probe was calculated from first principles and the geometry of the pickup was adapted to maximize the signal for a beam with a 72 MHz structure. At the second harmonic a signal of 30 nV per nA of proton beam is expected.

Preamplifier and signal line

Although a low noise, very strong shielding semi rigid cable is used for the signal transfer from the phase probe to the read out electronic, a preamplifier with 22 dB gain was used to filter and enhance the signal before noise and Rf disturbances are added along the cable. Additionally, the prefiltering and the directivity of the preamplifier prohibit the build up of standing waves of all harmonics which are rejected at the entrance of the read out electronic.

Data acquisition unit and control computer

The design of the electronics is based on a PSI concept [3] and further developed to enable measurements with very low proton currents. Fig. 1 shows the schematic arrangement of the preamplifier and the data aquisition unit. In the latter the incoming measuring signal is filtered several times to pass the 144 MHz portions and to block the fundamental frequency, the third and all higher harmonics. The rejection of these harmonics is more than 60 dB. A large amplification of +50 dB is realised for the second harmonic in three fixed stages. Two additional stages in the I/Q-demodulator can be switched on by the control software and enhance the amplification to +82 dB.

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Control Software

The control code is based on National Instruments LabVIEW™ and allows an automatic run of the measuring procedure. It can be started and stopped from the main control system over a profibus interface. In addition to that it is possible to change all of the program parameter at the local control computer.

At the beginning of a measuring loop the control program at first adjusts the variable amplification stages of the I/Q-demodulator. This is done on the basis of the voltage pulses. Then the rough I/Q data can be measured. The amplitude of the incoming measuring signal is calculated from these data after a digital filtering, which is necessary to supress the noise e.g. from the mains. This digital low pass filter has an adjustable bandwidth and steepness. For a precise determination the phase value is calculated and averaged over a series of I/Q data.

RESULTS

Laboratory tests were performed for which the first harmonic (reference line) and the second harmonic (probe signal) were generated as sinus signals by means of a Network Analyzer. To simulate the real cyclotron including RF disturbance an interferer of -80 up to -60 dBm was introduced in the signal line.

Table 1 summarises the technical specifications of the phase-detecting system which arised from these tests in the laboratory. Taking into account a sensitivity of the capacitive pickup probe of 30 nV per nA of proton beam current, the minimum input power of -130 dBm corresponds to a beam current of 3.3 nA.

Table 1: Technical specifications of the PHD system without disturbances.

Signal Channel	
Frequency of detection	144 MHz
Harmonic Rejection	> 60 dBc
Dynamic Reserve	70 dB
Input Power	-60 ÷ -130 dBm
Phase Range	180° at 72 MHz
Phase Absolute Error @ P_{max}	< ±0.1°
Phase Absolute Error @ P_{min}	< ±1.2°
Amplitude Accuracy @ P_{max}	±1 in the 4th digit
Amplitude Accuracy @ P_{min}	±1 in the 2nd digit
Digital Filtering (low-pass)	
Bandwidth (variable)	≤ 1000 Hz
Filter Order (variable)	≥ 3

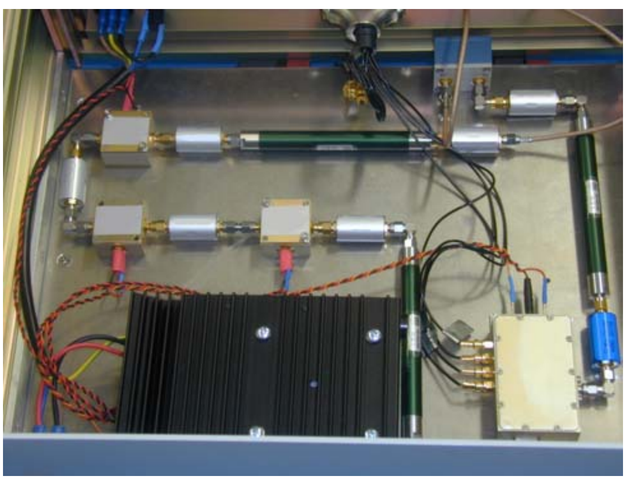

Figure 2: Interior view of the data aquisition unit of the PHD system

Further tests at the Julic cyclotron were performed in several ways. These results showed clearly that

- The use of an appropriate preamplifier at the detector output is necessary.
- The matching of the RF-line from the first part of the detector up to the PHD is a very critical issue, because the second harmonics from "echo" peaks due to reflections introduce errors.
- A "beam on/off" calibration is necessary. So during the calculation of amplitude and phase the offset value, which can be measured in the situation "beam off", will be taken into account.
- A phase range of 360° at detection frequency of 144 MHz (180° at 72 MHz) is necessary to avoid disturbance induced phase jumps which would by the case if I/Q-demodulation would be based on a flip flop trigger technology.
- For the digital post processing low pass filtering is better than Kalman-filtering or averaging.

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