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Nondestructive intensity monitor for cyclotron beams

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For any experiments that use beams of an accelerator, monitoring the beam intensity is always an important concern. It is particularly useful if one can continuously measure the beam current without disturbing the beams. Counting elastic scattering particle from the target is often used for such a purpose, however, the dynamic range of measurable beam intensity is limited and the calibration often changes for different experimental conditions.

We report here on the test experiments for a nondestructive current monitor of cyclotron beams using a toroidal pulse transformer. The principle of the transformer detector is shown in Fig. 1. The cyclotron beam is a single-turn "coil" of the primary side of the transformer which induces a magnetic flux in the toroidal core, then it induces a current in the secondary coil. In case a secondary coil of 5 turns is used, the transformer yields a nominal signal amplitude of

$$V_{\mathrm{sig}} = \frac{I_{\mathrm{beam}}}{5\ \mathrm{turns}} \left(\frac{1}{50\Omega} + \frac{1}{50\Omega} \right)^{-1} = 5\ \Omega \times I_{\mathrm{beam}} \quad (1)$$

at the 50 Ω input of the amplifier. The sensitivity of 5 nV/nA, is quite low to be measured in a noisy environment. However, since the beams from the cyclotron are a chain of short pulses with a constant repetition rate of ≈50 ns, synchronous detection with a spectrum analyzer or a lock-in amplifier can discriminate such a low-amplitude signal from the noise.

We used a Fast Current Transformer manufactured by BERGOZ Instrumentation, France. The transformer, model FCT-082-05:1-H-INS, consists of a toroidal core made of cobalt-based nanocrystalline and amorphous alloys of 82 mm inner diameter and a five-turn coil wound by the proprietary multithread technique. The bandwidth of the FCT is 32 kHz ∼ 700 MHz and the typical rise time is 500 ps. The fast response of the detector allows us to observe the higher harmonics of the pulsed beam. Since the duty cycle of the cyclotron beam is very low, typically <1/100, it generates many harmonics and the higher order harmonics have almost the same power as the fundamental one. It is advantageous to observe higher order harmonics, since the ambient noises are in general decreases with increasing frequency.

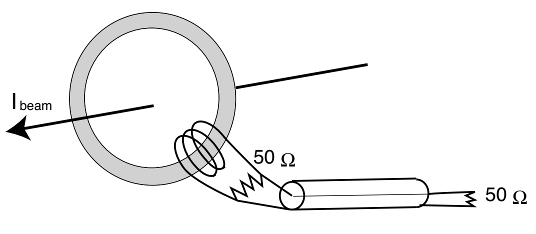

Fig. 1. Schematic diagram of toroidal current monitor. The beam current passing through the toroidal core is equivalent to the current in a one-turn coil.

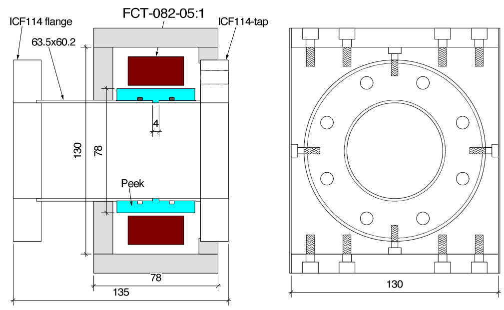

Fig. 2. Mechanical drawing of FCT monitor housing

The FCT is placed in the E6 beamline of RIKEN ring cyclotron. In order for the transformer to "see" a current passing through its center, the wall current imaging the ion beam must be diverted around the outside of the device. The beam pipe of 63.5 mm diameter is electrically interrupted by a PEEK sleeve for 4 mm width and the FCT is mounted close to the gap (Fig. 2). An aluminum box covers the FCT for electrostatic shielding as well as for electrical connection between the interrupted beam pipe outside of the FCT. The signal from the FCT is directly transported by a coaxial cable, SUHNER S10162B-11, for 70 m to the spectrum analyzer Tektronix 3056 or the lock-in amplifier, Stanford Research Systems SRS844, at control room J4.

Test experiments are performed using a cyclotron beam of 100A-MeV $^{13}C^{6+}$ with various beam intensities. Figure 3 shows a power spectrum of the second harmonics of the 14.5 MHz pulsed beam measured by the spectrum analyzer. In this measurement, the cyclotron beam was chopped with a 10 Hz repetition cycle so that sidebands at ±10 Hz were also observed. The background level here was ~ -115 dBm which corresponds to 0.4 μV ≈ 80 nA, which is not sufficiently small to observe low-intensity beams.

Use of a lock-in amplifier is more suitable for measurements of the absolute value of the current. A measurement for various intensities of ∼400 nA to ∼3 nA using the lock-in amplifier is shown in Fig. 4. The cyclotron beam was chopped with 0.01 Hz and a duty

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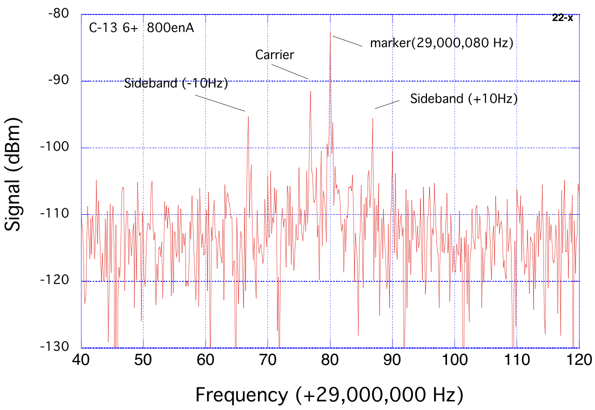

Fig. 3. Power spectrum of the second harmonics of 100A-MeV ^{13}C^{6+} beam of 800 enA detected by FCT. Sidebands due to a chopped beam with 10 Hz as well as the carrier signal at ∼29 MHz are observed.

cycle of 50% to enhance visibility. The rf signal of the cyclotron was used for the reference signal of the lock-in amplifier with the '×2' mode which corresponds to the second harmonics. Here, the background signal was as low as ≈40 nV, which enabled us to measure such a low-intensity beam of 3 nA.

The proportionality of the FCT signals with a background subtraction to the Faraday cup measurements preserved for wide range of intensity (Fig. 5). The gain factor and the background voltage obtained were 6.49(4) nV/nA and 39(1) nV, respectively.

Adjustment of the phase is essential for obtaining such a low background condition. The absolute amplitude of the output signal (dBm) was as large as ∼0.45 μV even in the beam-off period, which was mainly caused by a large phase-off component $Y = -0.45$ μV, while the phase-on component was $X = 0.04$ μV. This large off-phase signal, but still synchronized to the cyclotron beam frequency, is supposed to be due to the rf signal of the cyclotron which may come along the beam transport line. It can be a problem if the beam bunch and the rf noise signal coincide with each other. However, such a condition should be avoided by moving the location of the FCT, since the beam velocity ($\sim 0.5c$) and the traveling velocity of the rf signal should differ.

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References

1) BERGOZ Precision Beam Instrumentaion: Fast Current Transformer User's Manual.

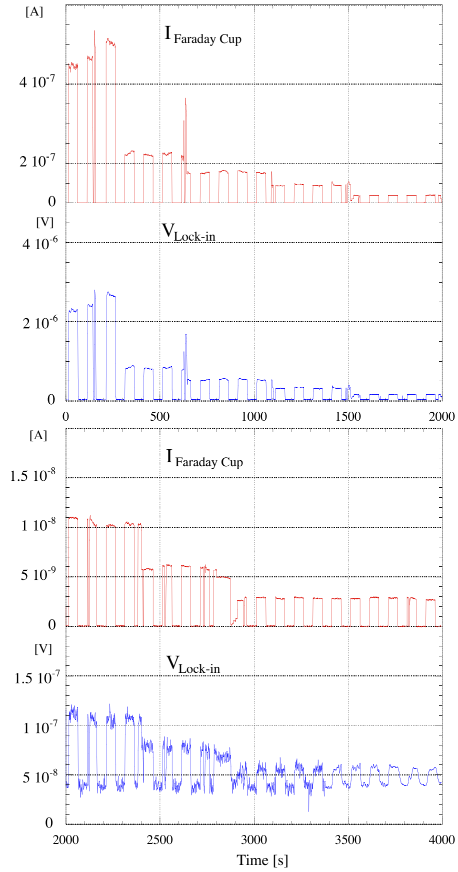

Fig. 4. Cyclotron beam intensities measured at a Faraday cup and voltages of the lock-in amplifier for various intensities. The time constant for the lock-in amplifier was 300 ms except for the last 5 peaks which were at 1 s (3 peaks) and 3 s (2 peaks).

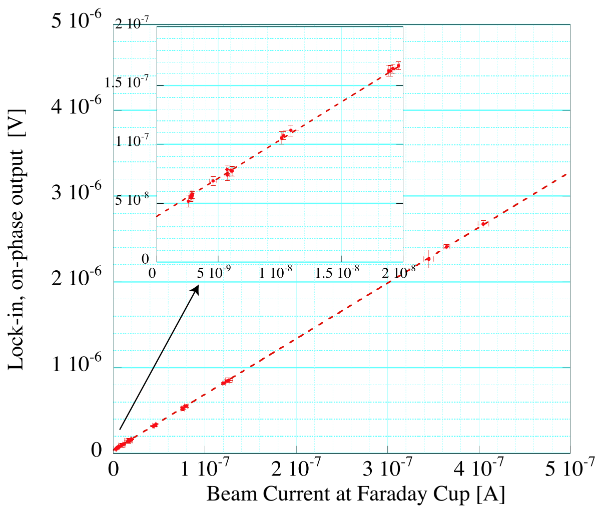

Fig. 5. 'On-phase' voltage of lock-in amplifier signal vs. beam current measured at Faraday cup. Insert is an enlarged graph for lower intensities. The fitting line is $y = 6.49(4) \cdot x + 39(1) \times 10^{-9}$