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NEW BEAM DIAGNOSTICS AT GANIL : VERY SENSITIVE CURRENT TRANSFORMERS IN BEAM LINES AND COUNTING SYSTEM OF BEAM TURNS IN CYCLOTRONS

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ABSTRACT

Two new beam diagnostics have been designed and are in operation at GANIL :
- To measure very small beam currents without intercepting the beam, transformers have been developped whose resolution is as low as 1 enA. That is obtained by ussing synchronous detectors locked on the PIG source pulsation and by reducing the noise level.
- As the accelerated orbits in the second main cyclotron are overlapping one another, we cannot count the number of turns by a classical moving probe. Therefore we compute the cross-correlation function of the beam signals detected on inductive probes at the input and the output of the cyclotron. Due to the natural random beam structure, this cross-correlation function has a sharp maximum for the value of the beam time of flight. Thence the right number of beam turns can be calculated.

INTRODUCTION

The GANIL complex is a heavy ion accelerator composed of 3 cyclotrons, the first one is compact and is followed by two identical separated sector cyclotrons (SSC), the ion charge state being increased by stripping between SSC's.

In order to tune and to control the machine more easily, we decided to design and set up non-interceptive beam diagnostics. Two of them are described here :

- Current transformers (CT) measure the beam average intensity with accuracy. Their resolution is expected to be less than 1 enA and their nominal range 10 eμA. They are used continuously during the normal operation instead of the Faraday cups.
- A SSC turn counter system computes the right number of beam accelerated turns inside the SSC. Up to now we have not been able to know it inside SSC2 by using the movable current probes, as the turns overlap one another (except for the extracted turn of course). The use of this system will save tuning time, even in SSC1 where turns are separated.

CURRENT TRANSFORMERS [1,2,3,4]

System description

A current transformer system consists of four parts (fig 1)

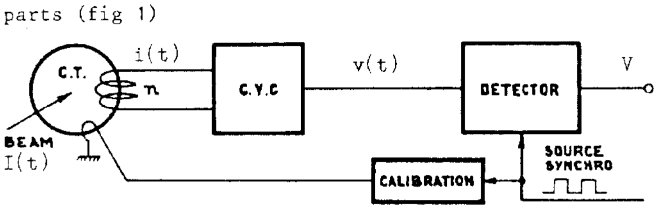

Fig 1 : *Current Transformer Block Diagram*

A Toroidal Core Current Transformer (CT)which gives i(t) in bandwith :

$$i(t) = \frac{I(t)}{n} + N_p(t)$$

with I(t) : the beam current, n : number of wire turns, $N_p(t)$ the noise picked up by the transformer.

A Current-to-Voltage Converter (CVC) which gives :

$$v(t) = Ri(t) + N_e(t)$$

where $N_e(t)$ is the electronic noise generated by the CVC

Therefore $$v(t) = R\frac{I(t)}{n} + N_v(t)$$

with $$N_v(t) = RN_p(t) + N_e(t)$$

A Detector which picks the beam average current out of v(t) : $V = k\ I(t) + N_D$

where N_D is the detected noise due to $N_e(t)$ and $N_p(t)$

As N_D is the resolution of the measuring device, we have tried to make N_D as small as possible.

A Calibration system which sends a calibrated current.

Choice of the detector

As the ions are produced by a pulsed PIG source, we have chosen to use a synchronous detector locked on the source frequency F (100 Hz to 300 Hz) (fig. 2)

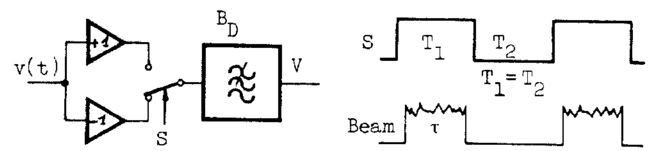

Fig 2 : *Synchronous Detector Principle*

The detector output V is proportional to the beam average current with the low pass bandwith B_D if :
- the beam time τ is completely within T_1
- the beam current frequency harmonics have not their phase shifted by the CT. The lower cut-off frequency B_T must consequently be low enough (about F/20, therefore B_T < 5 Hz).

The resolution is : $N_D r.m.s. = \overline{\frac{1}{k}N_v^{kF}}^2 \sqrt{B_D} \cong N_v^F \sqrt{B_D}$

where N_v^{kF} is the noise density of $N_v(t)$ for the odd harmonics k of the pulsation.

To reduce N_D, we have chosen B_D = 1 Hz and we have tried to reduce $N_p(t)$ and $N_e(t)$.

Another advantage of this detection is the alternating amplification which cancels the offset drift.

Choice of the CT and the CVC

Figure 3 shows the CT with the CVC :

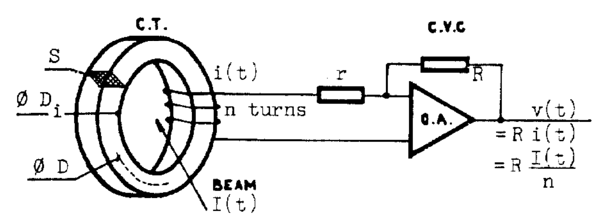

Fig 3 : *Current Transformer (CT) with its Current-to-Voltage Converter (CVC)*

The lower cut-off frequency B_T is : $B_T \sim \frac{rD}{\mu_r S n^2}$

We obtained $B_T \cong 1$ Hz with :
- $ØD_i$ = 80mm or 100mm according to the vacuum pipe
- S ≅ 40mm x 40mm
- $\mu_r = 10^5$. This value optimizes quite well $N_e(t)$ without increasing $N_p(t)$ too much.
- r = 1Ω. Decreasing r more makes the operational amplifier (O.A.) unstable in D.C.

The O.A. in use is BURR-BROWN OPA27. We obtained N_e^F < 4 μV/$\sqrt{Hz}$ for F = 200 Hz, which is equivalent to 0.6 enA of beam current with a bandwith of 1 Hz.

Mechanical assembly

Figure 4 shows how toroidal core is set up so as to reduce the noise $N_p(t)$ detected by the CT as efficiently as possible.

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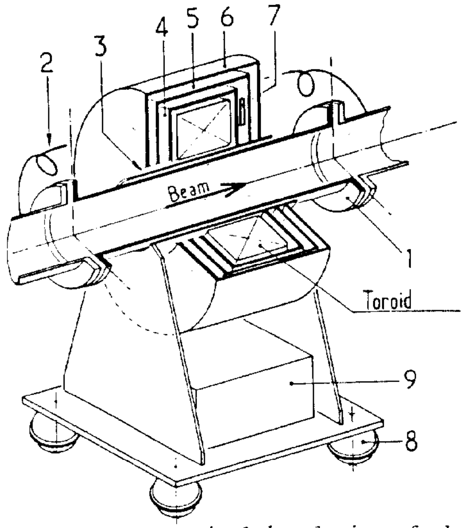

Fig 4 : *Current Transformer Assembly*

- an electrical insulation of the vacuum pipe (1) and a very low impedance shunt (2) cancel the parasitic current through the toroid.
- all current loops are removed (3)
- electromagnetic shieldings in soft iron (4) and in µmetal (5), and an electric shielding (6) in iron or in aluminum, protect the toroid and the CVC(7) against the parasitic electromagnetic fields. Unhappily, this protection is not quite efficient because of the hole for the beam.
- a very efficient suspension (8) damps any support vibrations which generate magnetic flux variations therefore parasite current a heavy mass (9) (∿ 30 kg) improves its efficiency
- the most difficult problem to solve is the noise current generated by microphonic effect because the noise level is high in the machine cave (90 dBA).

Actual performances

At present, four CT's are in operation. Two of them installed at the SSC output work as expected. Figure 5 gives the noise spectrum N_v^F before the detector and the resolution N_D versus the source frequency. The zero drift is very small (< 1 enA).

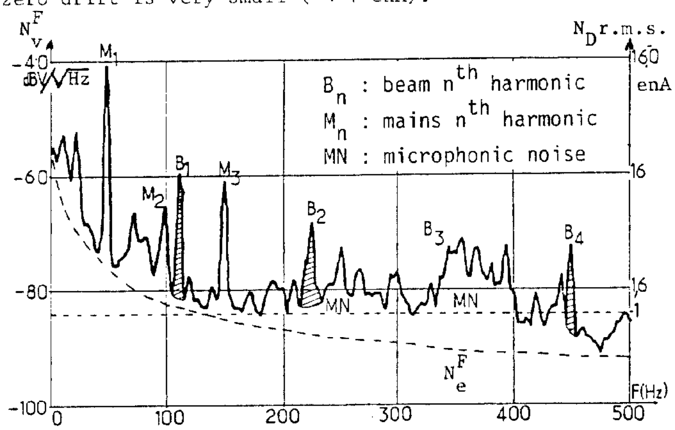

Fig 5 : *Noise Spectrum (N_v^F) and Resolution (N_Dr.m.s.) obtained with a 1 Hz bandwith*

The other two installed at the SSC input, are noisier (3 to 5 enA according to F) because they are bigger and therefore their shieldings are less efficient.

Improvements

In beam transfer lines between accelerator and experiment rooms, the beam current may be very small (<10 enA). The CT performances have to be improved consequently. We hope to improve their resolution down to 0.2 or 0.3 enA because all parts of the CT device can be still improved (microphonic effect in particular)

At the end of this year, the PIG source will be replaced by an external ECR source. Such a source is DC working or in a slowly pulsed mode, we plan to chop the beam after the source to be able to use the CT. It will be possible to choose the best frequency and to obtain an excellent resolution everywhere and everytime.

SSC TURN COUNTING SYSTEM

Principle

In theory : to calculate the number of turns inside SSC, we measure the beam time of flight λ between the input and the output of SSC in the following way : (fig 6).

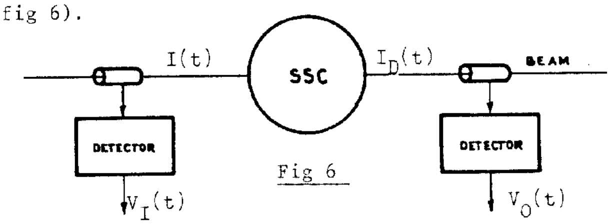

Fig 6

$$V_I(t) = K_I\{I(t) + N_I(t)\}$$

$$V_O(t) = K_O\{I_D(t) + N_O(t)\}$$

with $N_I(t)$ and $N_O(t)$: the noise generated by the detector ; $I(t)$ and $I_D(t)$: the beam intensities

If $\mathscr{C}_{XY}(t)$ is the cross-correlation function between X(t) and Y(t), and if $N_I(t)$ and $N_O(t)$ are white noises, we get : $\mathscr{C}_{V_I V_O}(\tau) = K_I K_O \mathscr{C}_{II_D}(\tau)$

As $I_D(t) = I(t-\lambda)$ and as I(t) has a natural random structure (see figure 7) $\mathscr{C}_{II_D}(\tau)$ has a maximum for $\tau = \lambda$

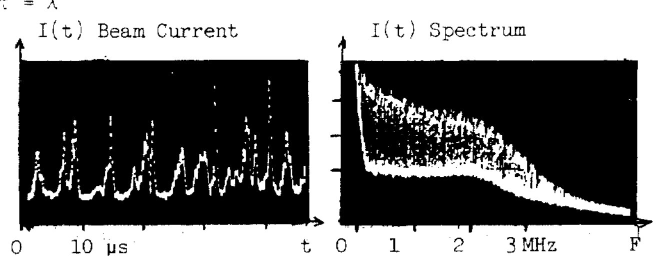

Fig 7 : *Beam random Structure*

Then, the right turn number TNB can be get by the relation : $TNB = \lambda/f - TNB_o$, where f is the revolution frequency and TNB_o the equivalent number of turns along the injection and extraction channels.

In practice : the expected measuring parameters are the following ones :

	TNB	λ (mean)	precision δ turn	δλ	f
CSS1	50 to 100 turns	∿ 50 µs	<1/2 turn	<250 ns	1MHz to 2MHz
CSS2	300 to 600 turns	∿ 100 µs	<1/2 turn	< 70 ns	3.5MHz to 7MHz

This precision of 70 ns requires that the frequency spectrum of I(t) therefore of $V_I(t)$ and $V_O(t)$ must be 2 MHz wide at least. As shown on figure 7, the beam intensity provided by the PIG source has an adequate frequency spectrum.

Devices description

Detector : we have used the existing beam central phase measurement device : capacitive probes and their processing units (amplifiers, filters and delay lines), signal reference and microprocessor control.[5,6] We have only added a synchronous detector working on the RF second harmonic and made of a mixer and a 3 MHz low pass filter to get V(t) (fig. 8).

The signal to noise ratio ($\frac{V}{N}$) depends on the beam energy W and intensity I ($V = kI/\sqrt{W}$ and N = preamplifier noise).

For instance, $\frac{V}{N} = 1$ for about 5 enA at the SSC1 input, 100 enA at the SSC2 output and 20 enA between SSC's.

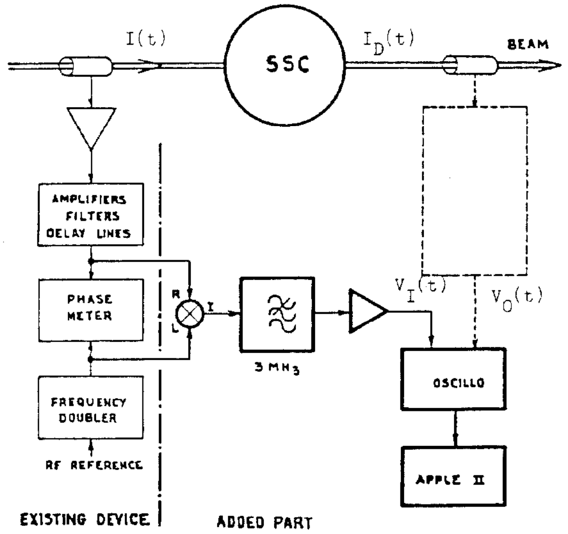

Fig 8 : *Turn Counting System Block-Diagram*

Cross-correlation computing : (τ = kT)

$$\mathcal{C} = \mathcal{C}_{V_I V_O}(\tau) \cong \frac{1}{2N+1} \sum_{n=-N}^{n=+N} V_I(nT)V_O(nT+\tau)$$

We use a dual trace 20 MHz digital storage oscilloscope for $V_I(t)$ and $V_O(t)$ recording and an APPLE II computer for correlation and number of turns computing.

At present, we record 1024 samples on each trace with a sampling period of 100 ns or 200 ns according to the value of λ.

The number of computed $\mathcal{C}$ values is 50 if the number of turns is roughly known (± 25 turns for SSC2 and ± 5 turns for SSC1). The number N of samples used to compute $\mathcal{C}$ is 400 and the computing time 30 seconds.

If the number of turns is not known at all, the number of computed values is increased up to 200 or more but the precision is worse (N is smaller) and the computing time is bigger (a few minutes).

In any cases, the correlation coefficient is computed for the maximum value of $\mathcal{C}$ because it is a measurement validity criterion.

Present Results

Counting the number of turns inside SSC2 is an easy operation and the results are good in most cases if the signal to noise ratio is larger than 0.5. That is obtained with approximatly 10 enA beam at the input and 50 enA at the SSC2 output. Figure 9 shows an example.

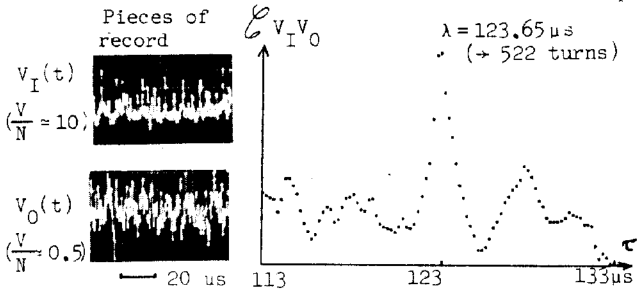

Fig 9 : *Example of Turn Counting (SSC2 with Kr ions)*

If the beam intensity is smaller, measurements becomes delicate.

When the beam intensity has a quite periodic structure, measurements may not be possible, the correlation function becoming periodic too. Figure 10 shows an example of this case. Happily, this is quite rare. In most cases there is a mixture of periodic and random structure depending on accelerated ions.

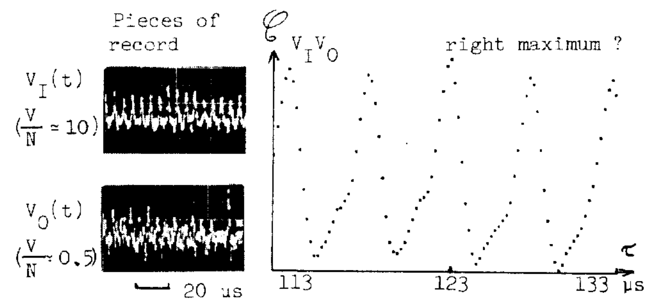

Fig 10 : *Turn Counting with a Beam periodic Structure*

Improvements

To improve the measurement accuracy in the limit cases (small intensity or periodic structure) we must increase the number of computing samples and reduce the sampling period. For that, we plan to use a numeric oscilloscope with 4 kwords per trace and a 50ns period sampling.

The present method can be used only when the beam is extracted from the cyclotron. A more convenient solution would consist of detecting the last turn intensity just before being extracted with an interruptive phase pick up located on a movable probe. Moreover, such a pick up is more sensitive than the SSC2 output capacitive probe. The first tests are in progress.

When we use an external ECR source, the beam intensity will not have sufficient random structure to use this measurement system directly. We plan to create a specific random structure during the measurement time by modulating the RF level of the non-resonant buncher which is located between the ECR source and the injector.

REFERENCES

{1} S. Battisti,"Etude des transformateurs de mesure", CERN Report, CERN/MPS-CO/69-15

{2} J. Borer and R. Jung, "Diagnostics", CERN Report, CERN/LEP-BI/84-14

{3} R. Steiner, K. Merle, H.G. Andresen, "A high Precision Ferrite-Induction Beam Current Monitoring System", Nucl. Instr. and Meth,Vol 127, pp 11-15, 1975

{4} M. Bergher, "An absolute Calibrator for DCI Beam Current Monitors", IEEE Trans. NS28, n° 3, pp 2375-2376, June 1981

{5} A. Chabert, F. Loyer, J. Sauret, "Beam Tuning and Stabilization using Beam Phase Measurements at GANIL" Proceedings of the 10th Int. Conf. on Cycl., East Lansing US, 1984

{6} F. Loyer et al, "Diagnostics de faisceau : Mesure de la phase centrale", GANIL Report GANIL 83R/010/CC/01, 1983