Low Intensity Beam Charge Measurement of the 1GeV/amu SATURNE II Extracted Beam

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Abstract

The SATURNE II synchrotron provides a large variety of ion species, and a wide range of energy. Beams from 10^8 to $6x10^{11}$ elementary charges can be ejected during a typical 500 ms duration spill. Absolute measurement of the ejected charges leads to detect very low currents ($\leq 10^{-7}$ A). These beam characteristics have needed to build a high sensitivity intensity transformer (noise : down to $80x10^{-9}$ A, bandwidth : 1Hz- 3kHz) whose function is to calibrate a secondary emission chamber (SEC) during a fast beam extraction process (3ms). This process achieved by four fast quadrupoles, increases the ejected beam current up to few 10^{-6}A. Then the SEC can be calibrated down to $5x10^9$ charges per spill (accuracy : ≤ 5%). During the standard slow extraction, the number of charges is provided only by the SEC whose sensitivity is $5x10^8$ charges.

1. INTRODUCTION

The proton and heavy ion SATURNEII synchrotron accelerates particles produced from three sources:

AMALTHEE : protons, deuterons, ^{3}He, ^{4}He.
HYPERION : polarized protons and deuterons.
DIONE : heavy ions (Li, C, N, O, Ne, Ar, Kr).

Then the particles are injected into the MIMAS accumulator-accelerator synchrotron (40 MeV protons) and accelerated through SATURNE II. The extraction energy can be tuned from 100 MeV to 2900 MeV for protons, and from 50 MeV to 1150 MeV for heavy ions (Q/A=0.5). The extracted beam intensities range from 10^8 elementary charges (heavy ions) up to 6.10^{11} (protons). The spill duration time is usually 500 ms, so the absolute measurement of the beam intensity leads to measure currents from 30pA to 200nA. Taking into account the various types of beams, their energies, their spill frequency spectra, their intensities, it came out that a single detector seemed impossible to be designed to achieve these absolute measurements. To reach them, a double detector system based on a secondary emission chamber (SEC), relative monitor to be calibrated, and on a beam current transformer (BCT) used as an absolute charge monitor, had to be built. Due to the low intensity levels to be measured, and the lack of high frequency components in the spill, the standard slow extraction system had to be changed to shorten the spill duration and therefore to increase dramatically the current measured with the BCT.

2.MEASUREMENT PROCEDURE

2.1 Extraction modes from SATURNE II.

a) Slow extraction mode : The beam is extracted from SATURNE II by using the third integer resonance $\vartheta_x = 11/3$. The beam blow up is controlled by sextupoles: two for the chromaticity tuning, and two to modify the stop-band. The particles are pushed into the resonance region by betatron acceleration, performed with a magnetic flux variation in a 10 tons iron core. For a constant voltage applied across the core, the spill profile is gaussian.

b) Fast extraction mode: Instead of pushing slowly the beam on the resonance line $\vartheta_x = 11/3$ it is moved quickly on this line with additional fast quadrupoles. The faster the variation of the quadrupole currents is, the shorter the spill.

2.2 Beam intensity measurement procedure.

a) The fast extraction is switched on. The BCT measures the extracted beam current which may then reach several μA. Simultaneously, the same spill current is measured by the SEC (fig.1). After signal processing, the SEC calibration coefficient is calculated.

b) Coming back to the standard extraction process, the BCT cannot work any longer but the previously calibrated SEC is able to provide the charge number.

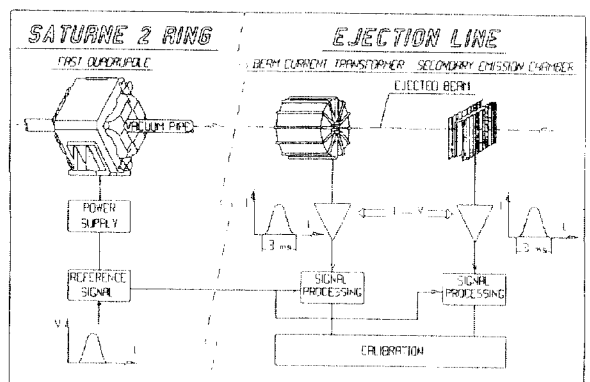


Fig.1: Diagram of the beam charge measurement system

3.THE DETECTORS

The intensity range of beams leads to design detectors as sensitive as possible. Therefore, it is essential to maximize the signal to noise ratio (SNR).

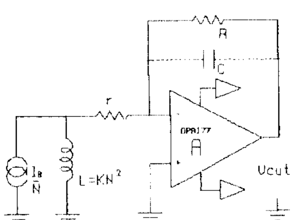
3.1 Beam current transformer.

a) Bandwidth.

Fig.2a shows the classical equivalent circuit of a BCT associated with its current amplifier. Assuming that the beam provides always an ideal coupling to the transformer which is considered as electrically perfect, the output voltage for an infinite gain operational amplifier is :

$$V_{out} = -\frac{R I_B}{N} \frac{L}{r} \frac{s}{1+\frac{L}{r}s} \qquad \text{with } s = j.\omega \qquad (1)$$

and the open-loop gain A fulfils the condition $\frac{R}{A+1} << r + Ls$. The droop time constant is $\tau = \frac{L}{r}$ (A = ∞) or $\tau = \frac{L}{r+\frac{R}{A+1}}$ (A finite). τ must be 100 times greater than a rectangular input pulse duration in order to keep the measurement error below 1%. The upper cut off frequency is determined by the capacitor C in parallel with R or by the stray capacitance.



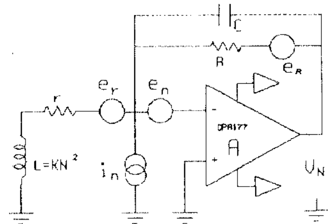


fig.2a:BCT equivalent circuit fig.2b:Noise equivalent circuit

b) Noise.

Fig.2b shows the modeled noise equivalent circuit. All the noise sources are uncorrelated. Their power spectral density are E_n^2 and I_n^2 for the operational amplifier, E_R^2 and E_r^2 for the resistors. Assuming that Aβ>>1 (β: feedback factor), the noise output rms voltage is determined by intregrating the sum of the products of each noise power spectral density generator by their associated closed-loop transfer function over the bandwidth. The combined value is :

$$V_N = \left[\int_{\omega_0}^{\omega_2}\left[E_n^2.|H_{En}|^2 + I_n^2.|H_{In}|^2 + E_R^2.|H_{ER}|^2 + E_r^2.|H_{Er}|^2\right]d\omega\right]^{\frac{1}{2}}$$

where the integration domain may be limited to (ω_0, ω_1) for the operational amplifier flicker noise and to (ω_1, ω_2) for the white noise (ω_1 is the corner frequency).For an input signal I_B whose frequency is in the BCT bandwidth, the SNR is :

$$SNR = \frac{R.I_B}{N} \cdot \frac{1}{V_n} \qquad (2)$$

The analytic calculation of equation (2) shows that the SNR depends on both N and R when τ is kept constant :

-The higher the resistance R is, the higher the SNR.

-For each R value corresponds a N value which maximizes the SNR.

To verify the method, the computation has been done for a bipolar input operational amplifier : OPA177 (fig.3).

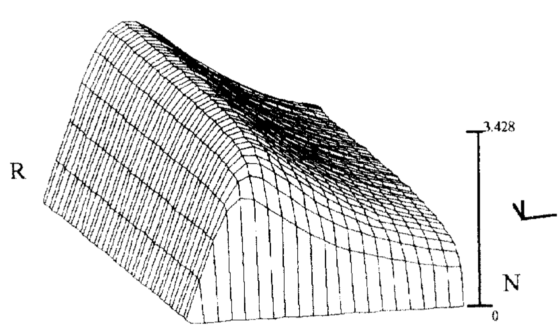


Fig.3: BCT SNR versus R and

For instance, selecting R=$10^7\Omega$, L=130H and I_B =100nA, the SNR is 3.5 in a 1Hz-3KHz bandwidth range.

They are other sources of noise such that:

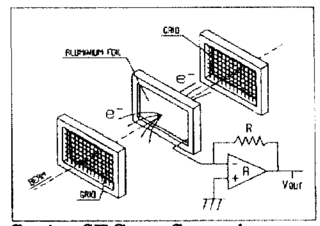
-The electromotive force which appears at the coil terminals due to their motion in external magnetic fields existing in the accelerator environment. To minimize this source of noise, the BCT is decoupled from local vibration sources with very efficient isolators.

-Even though the BCT is firmly fixed, any form of coupling with external electromagnetic fields must be avoided : the BCT has to be shielded.

3.2 Secondary emission chamber.

a) Principle.

When a beam goes through a SEC (fig.4a), low energy electrons are emitted from both sides of the central foil and collected by positive voltage biased electrodes.



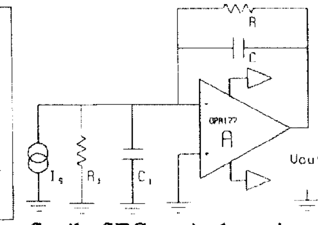


fig.4a: SEC configuration fig.4b: SEC equivalent circuit

A rule of thumb predicts that the electron production efficiency η is proportional to the energy beam mean loss according to the BETHE-BLOCH formula. For 10^{11} protons (1GeV, 500ms) the secondary electron current is $I_s \approx 1nA$ ($\eta \approx 3\%$).

b) Signal to noise ratio.

The operationnal amplifier is connected in a current to voltage converter configuration (fig.4b). R_i and C_i are the interelectrode resistor and capacitance. The output voltage is $V_{out} = -R.I_s$(either with A=∞, or $\frac{R}{A+1} << R_i$). The upper cut off frequency is $f = \frac{1}{2.\pi.R.C}$. The SEC SNR is calculated in the same way than for the BCT, keeping f constant (fig 5) for a FET-input electrometer amplifier (OPA128) in the 10^{-5}Hz-3KHz bandwidth range (fig.5).

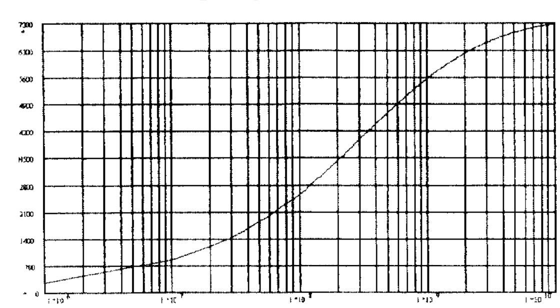


Fig. 5: SEC SNR versus R

For I_s=1nA, R=$10^9\Omega$ the SEC SNR $\approx$ 5600

4. INSTRUMENTATION DESCRIPTION, RESULTS

4.1 Fast extraction.

Four series connected ironless fast quadrupoles located in the main ring are used to change the tuning ($\Delta\vartheta_x$ = .04 at 2GeV). Their power supply is controlled by a programmable function generator, giving a 6 ms length positive half sine signal for a 3ms spill duration. It takes only few minutes to change the extraction mode.

4.2 Beam current transformer.

The SNR studies point out the need for the highest possible self-inductance of the BCT. In our case it is mounted on a chassis sustained by four pneumatic vibration isolators whose resonance frequency is 1.5Hz and its self-inductance is 128H with $K=2.10^{-4}$, od : 240mm, id : 130mm, h : 40mm, N:770 turns. The shielding thickness has been pre-determined with CODWELL diagrams [1] and checked by experimental measurements. It is made of mu-metal and Armco for magnetic shielding and copper for electrical shielding.

4.3 BCT electronic design.

To select the best input operational amplifier we have to evaluate the contribution of each E_n^2 and I_n^2 to the output signal noise voltage. Simulations with SPICE code lead to choose bipolar input transistor operational amplifiers. They confirm the SNR results shown in (fig.3).

The signal is then amplified with a programmable instrumentation amplifier (Gain :1-10-100-1000).The signal ohmic continuity is broken by using an isolation amplifier before the analog differential transmission to the main accelerator control room.

The output noise is 80nA peak to peak in a 1Hz-3KHz bandwidth ($R=10^7\Omega$, $C = 5$pF).

4.4 SEC electronic designs.

The current levels to be measured impose a FET input electrometer operational amplifier as first stage. In order to keep good performances, careful layout, input leakage current minimization and shielding are required.

Two preamplifiers, multiplexed by a high quality relay, are used: one for the fast extraction mode (Gain = 1V/μA, $R=10^6\Omega$), the other for the slow extraction mode (Gain=1V/nA, $R=10^9\Omega$). They are followed by an instrumentation programmable amplifier (Gain: 1-10-100).

The output noise of the first channel (calibration channel) is 30pA peak to peak (bandwidth:0-3KHz) .

4.5 Signal processing (SEC calibration).

In the main accelerator control room, SEC and BCT analog signals are filtered (BCT:1Hz-3KHz, SEC: 0-3KHz) and digitized (12-Bit) at the rate of 1 Megasamples/s by a CAMAC waveform recorder (LECROY 6810). Digital data are transmitted to a PC computer via a GPIB interface module. The SEC calibration sequence is the following :

-An external trigger opens a 8 ms duration rectangular window for signal recordings (fig.6).

-Two ms after the trigger occurs, the 4 fast quadrupoles power supply is swichted on.

-A sequence of 20 successive spills are recorded simultaneously with the SEC and BCT.

-Both SEC and BCT average signals are computed. Therefore, high frequency components are reduced: BCT noise decreases down to 20nA peak to peak ($\approx 3.10^8$ charges).

-During the first and last ms of the rectangular window, the offset is measured and the signal base line restored: D.C errors are virtually eliminated.

-The integrals of these resulting signals are computed. The charge number is calculated from the BCT integral, and the SEC calibration coefficient deduced.

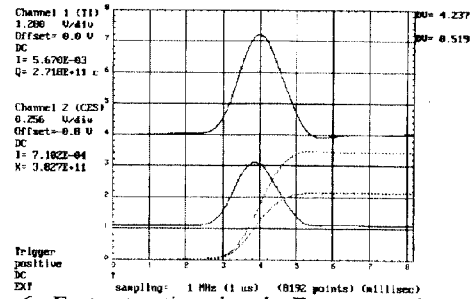


Fig.6 : Fast extraction signals. From top to bottom : BCT spill signal, BCT signal integration, SEC spill signal, SEC signal integration.

4.6 Slow extraction charge measurement.

The SEC highest sensitivity channel is now switched on (Digitizing rate : 10Ksamples/s), and the bandwidth reduced down to 300 Hz. Total noise is 0.5pA peak to peak, corresponding approximatively to several 10^7 protons at 1GeV. Because of its low optical disturbances caused to the beam, the SEC is maintained on operation and gives, after signal integration, the charge number of each spill.

5.CONCLUSION

This beam charge measurement system has been working in routine for two years. The performances are very close to the calculated ones. Over a long period in the same vacuum conditions the SEC calibration remains stable ($\approx 5\%$). SEC electron emission efficiency measurements for SATURNE II beams are in progress. At last, this system is powerfull to measure the beam extraction efficiency of SATURNE II which reaches now 80%.

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