CURRENT TRANSFORMERS FOR GSI’S KEV/U TO GEV/U ION BEAMS - AN OVERVIEW

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Abstract

At GSI's accelerator facilities ion beam intensities usually are observed and measured with various types of current transformers (CT), matched to the special requirements at their location in the machines.

In the universal linear accelerator (UNILAC), and the high charge state injector (HLI) as well, active transformers with 2nd-order feedback are used, while passive pulse CTs and two DC-CTs based on the magnetic modulator principle are implemented in the heavy ion synchrotron (SIS) and the experimental storage ring (ESR). In the high energy beam transfer lines (HEBT) the particle bunch extraction/reinjection is monitored with resonant charge-integrating types.

Since more than 10 years number and significance of beam current transformers for operating GSI's accelerators have grown constantly. Due to increased beam intensities following the last UNILAC upgrade, transmission monitoring and beam loss supervision with CTs have become the main tools for machine protection and radiation security purposes.

All CTs have been constructed and developed at GSI, since no commercial products or were available, when solutions were needed.

1 INTRODUCTION

In GSI's various accelerators a large range of ion species are handled, from protons to uranium, including a lot of isotopes and nearly all possible charge states. The peak beam currents in the SIS in the meantime have grown up to nearly 1 Ampere, reaching the space charge limit with Ne^{+10}, while still experiments with less than one μA are performed with low energy beams in the UNILAC. The time structures of the different beams spread from 10^{-9} to more than 10 seconds, and often have to be resolved and displayed.

CTs built from high permeability tape-wound ring cores have replaced most of the faraday cups in the UNILAC, because they do not destroy or even influence the beam, and do not suffer from beam power load. Their output exhibits no dependence to the beam's position or extent.

Their most important characteristic feature is their inherent and reliable calibration, if careful design and construction are applied.

2 LINAC TRANSFORMERS

2.1 Electronic and magnetic layout

Up to 15 different machine settings with respect to ion energy or species can be treated in a periodically pulsed sequence. Typical macropulse duration of the ion sources and linacs between 50 μs and 8 ms demand rise times about 1 μs, and negligible pulse droop losses to guarantee accurate measurements. The RF cavities are operated at 36 and 108 MHz, with bunch widths of about 1 ns FWHM, respectively. As this would require more than 1 GHz bandwidth, beam energy (Time-Of-Flight), energy spread, longitudinal emittance and beam position measurements are performed with a system of capacitive pick-ups installed along the machines, so transformer bandwidth can be kept around 500 kHz. At present 38 CTs are installed in the linac sections and the low energy experimental areas.

Each CT's crossed-differential winding is connected to the front electronics, mounted as close as possible to the beam pipe. By those means excessive noise or hum pickup is reduced. A current-to-voltage converter with a second-order current feedback network [1], range selection and a switched clamp for baseline restoration are installed in the front box. The analogue output signals are then transmitted via differential and terminated twisted pair lines to their associated integrating digitizers [2]. These again are installed in a central control station outside the linac tunnel, keeping the cable lengths below 100 meters. Via special interfaces, a multiplexer and a PC equipped with an ADC plug-in, 2 of 64 CT pulse signals can be selected for display on the PC screen.

This feature enables the machine operators to observe any modulations on the macropulse, like plasma fluctuations in the ion source, or settling problems of the RF cavity amplitude controllers induced by beam loading.

A/D-conversion of the CT signals is performed by an U/F-converter with 8 MHz maximum frequency, feeding a 16-bit digital counter. In the lowest current range one count equals a charge amount of 0.6 pC. By gating the counter with a trigger interval congruent to the beam pulse, the pulse charge can be read as the counter end value. This is transferred to the control system together with the gate length value (measured simultaneously), and a simple calculation returns the average beam current and the number of particles in the CTs for all sequential beam pulses. The results are displayed as bar graphs or trend plots in the operating programs.

Tab. 1: Main specifications of linac CTs

Ranges	5, 10 μA ..... 100mA full scale
Resolution	200nA rms, full BW
Risetime	< 2 μs
max. pulse length	6ms for droop error < .5%

When the upgraded UNILAC is operated at highest intensity level, the pulse power for Uranium-Ions accelerated to 11.4 MeV/u will exceed 1 MW. Under this conditions, a single beam pulse of 100 μs will destroy the wires of a profile harp or even will melt the beam tube wall. As a consequence, a beam loss controlled protection system was installed.

Starting after the injector section, all CT front electronics are equipped with an additional analogue output with a fixed transimpedance. The signals of two consecutive CTs at each case are fed into a dual-U/F-converter. Each pulse from the first converter channel triggers an up-counter, the corresponding down-counter is driven by the pulses from the successive CT. When this action is started and reset with a signal congruent to the desired time interval, the counter's value represents the instantaneous beam charge lost between the CT pair. If the value exceeds a threshold preset by the control system for each machine setup and monitor location, an interlock line is activated and the beam pulse length is shortened automatically with the beam chopper. This protective state is kept until the loss falls below the threshold again, whether by operator's intervention or by chance. With respect to electronic response times and the distance between the chopper and the respective transformer pair reaction times ≤10 μs are achieved.

Tape-wound ring-cores made from crystalline Supermalloy® or amorphous VITROVAC® are used for all CTs. These alloys exhibit highest initial permeability μ_i, improving signal-to-noise ratio in combination with a negligible magnetostriction coefficient λ_s, which helps to reduce microphonic noise produced by mechanical vibrations. Nevertheless, the cores fabricated from crystalline material had to undergo an initial demagnetization process. In most cases the noise, mostly induced by line-asynchronous motors of the vacuum pumps, could be reduced below 1 μA rms.

2.2 Mechanics, shielding and vacuum

A standard type with 48mm aperture diameter, an overall length of 100mm, and with DN100CF flanges commonly used in the linacs, was the first development. Some special versions with apertures up to 100mm or reduced length followed, solving problems with beam envelope clipping in the injector sections, or due to limited installation space between the RF cavities.

All transformer housings are fabricated from a ferritic stainless Cr-based steel. This material combines reasonable magnetic shielding efficiency with good surface properties for high vacuum usage and mechanical strength. A drawback has to be mentioned - it is not suitable for welding or brazing processes. Thus a single O-Ring breaks the wall mirror currents, and acts as a vacuum seal. The ring core is supported inside the housing by rad-hard foam strips, whereas mechanical stresses and vibrations are avoided.

3 TRANSFORMERS FOR SIS AND ESR

In the SIS the CTs have to solve two tasks. A fast CT [3] is used for multiturn-injection observation, while DC-CTs [4] based on the well-known fluxgate principle measure the accelerating ramp, the interval with a coasting beam, and while the intensity decays during slow extraction. The regular acquisition times are below 15 s, but can rise to minutes or even hours, if beam is accumulated and stored in the ESR, or lifetime measurements during e^--capture are performed in the SIS.

The cores for all versions are made from VITROVAC® with an inner diameter of 260mm and 10 mm^2 cross section.

3.1 Fast CT

The fast CT is a passive type with 100Ω termination, followed by a gain switchable amp and a fixed-rate ADC. As usual the signals from the front electronics are transmitted via differential lines to the control rooms Neglecting eddy current time constant τ_E and the secondary stray inductance, the output response equals

$$U(t) = I_b R/n * \exp(-t/\tau_L) \quad \text{if} \quad \tau_E << \tau_L \quad (1)$$

with

I_b = beam current
R = termination impedance
N = number of secondary turns
L = secondary inductance
τ_L = L/R = inductive time constant
τ_E = eddy current time constant

Tab.2: Main specifications for fast CTs

ranges	8, 100 μA ..... 300 mA f. s.
resolution	5 μA rms, BW = 1MHz
risetime	~500 ns
max. pulse length	100 μs for droop error < 10%

3.2 DC-CT

SIS and ESR each are equipped with a DC-CT [5], based on an identical design, but with some appropriate modifications.

The SIS type has been trimmed for fast response and low noise by adding a ripple reduction technique with an ADC/RAM/DAC-system. The ESR type was optimized for DC stability by a selected core pair and limiting the bandwidth with a sampling filter. Both CTs recently were extended with a voltage-to-frequency converter, providing a range-independent output.

The DC-CT core stacks are mounted in a bakeable and shielded housing, which is also used for the fast CT in the SIS. A 19" rack close to the beam tube contains the analogue station, equipped with differential signal transmission and processing.

Tab. 3: Main specification for DC-CT (SIS)

ranges	8, 300 μA .... 1 A f. s.
resolution	2 μA rms, BW = 20 kHz
risetime	< 20 μs
offset stability	±2 μA @ auto zero mode, <15μA/day
temp. coeff.	~1.6 μA/°C
mod. ripple	≤5 μA pp @ 2 kHz

4 HEBT TRANSFORMERS

4.1 Principle and Electronics

If particle bunches are extracted from SIS or ESR in the fast mode, their ionic charge as well as the transmission efficiency in the beam lines are monitored with CTs based on a parallel-resonant working principle [6]. After one to four bunches have passed, the circuit behaves as an exponentially damped oscillator. The circuit's terminal voltage at the first extremum is approximately:

$$U(\tau)= Q/nC*(1- \omega^2\tau^2/24) \quad \text{if } \tau < .1*T \qquad (2)$$
$$= Q/nC*(1- 1.6\,(\tau/T)^2)$$

with

Q = primary pulse charge

$\omega = 2\pi/T$ resonance frequency

τ = pulse duration, independent on time structure

n = number of secondary turns (100)

C = effective parallel capacitance

The transformer core is equipped with a crossed-differential winding, forming the inductor of the resonant circuit. A ferrite ring with μ_i=2200 and an inner diameter of 165 mm to fit over the DN100 beam pipe was chosen because of it's low parallel loss impedance at the frequencies of interest, and lower costs. The circuit is tuned to ~18 kHz, resulting in an integration error less than .2 %.

The CT's signal is routed to a front electronic block as close as possible to the core housing. It consists of an instrumentation amplifier, a 1...70 kHz bandpass, a gain programmable amp and a peak detector (PD), which was chosen for circuit simplicity (no bunch-synchronous timing necessary, averaging techniques not adequate for transmission monitoring). It's noise rectification characteristic turned out to be insignificant. Signal transmission via differential line drivers is as usual, range switching and PD reset are done from control electronics located far from the beam lines; the measured values are displayed by bar graphs in the control room.

Tab. 4: Main specification for HEBT CTs

ranges	4, 1 nC .... 1 μC
resolution	10 pC rms, or <1% f.s.
max. bunch width	1.5 μs total

4.2 Mechanics, shielding and vacuum

All HEBT CTs are operated under UHV conditions, which required appropriate materials and fabrication processes. A ceramic wall gap as well as metallic seals and baking jackets are implemented. The core is surrounded by a double μ-metal shield against magnetic interference.

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