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Technical Note ICT / 06.1

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INTEGRATING CURRENT TRANSFORMER (ICT) PULSE CHARGE ACCURACY

The Integrating Current Transformer was designed to measure the electric charge of every beam bunch in the CERN/LEP electron/positron collider. Klaus Unser who invented it published its conceptual design at the 1989 Chicago Particle Accelerator Conference: Design and preliminary Tests of a Beam Monitor for LEP
http://accelconf.web.cern.ch/AccelConf/p89/PDF/PAC1989_0071.PDF
Since the early installation of four ICTs on LEP, the instrument became a de facto standard for ultra-short pulse charge measurement in linacs, transfer lines, synchrotrons, slow extraction for medical purposes, calibration of medical ionisation chambers and more recently for laser-plasma / wakefield accelerators.

It has been a constant effort to establish the ICT measurement reliability for pulse or bunch electric charge. Laboratory measurements have been limited by pulse generator performance to 50ps risetime.
The homogeneity of the measurement inside the ICT aperture was first established to be better than 0.1% within the innermost 1/3 of the ICT aperture area. The ICT sensitivity was observed to increase as the axis of current moves closer to the ICT connector. At the inner edge of the ICT aperture, close to the connector, up to 2% excess reading can be observed. This is still the case today in spite of our research on alternative winding techniques.

The pursuit of absolute calibration led us to learn from private conversations with NIST that subnanosecond pulse charge standards are not better than +-1%.

This effort was shared by others who have good reasons to be concerned with the ICT accuracy. So its measurements were compared to other measuring methods.

Confidence in the ICT is of primary importance to radiological treatment, because ionisation chambers used in cancer treatment must be calibrated over a wide range of energy and dose rate. Energy of interest starts well a few MeV for eye tumors and reach >250 MeV for deep-seated tumors. To gain confidence in the ICT, METAS, the Swiss Standards Institute, cross calibrated the ICT and BCM-IHR vs. a water pool calorimeter large enough for all energy in the particle to be lost in the water. This is important, because the interaction cross section is not well known at every energy level. Integrating all the energy makes the measurement independent of the water cross-section vs. energy. The ICT showed excellent agreement with the calorimeter. The set-up now constitutes the Swiss primary standard for irradiation, based on the ICT measurement. It has been in service for many years. It is used by most European countries which don't have their own. Unfortunately, Gerhard Stucki who developed this primary standard has not yet published a paper.

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Other groups use the ICT to make absolute charge measurements. The TARC project headed by Carlo Rubbia of CERN/EET needed a precise count of particles injected in a subcritical reactor heart to study adiabatic resonance crossing. To gain confidence in the ICT (and BCM-IHR) they compared it with aluminium foil activation. They concluded that ICT and foil agreed to within 5%, and the margin of uncertainty is attributable to the aluminium cross section uncertainty: J.-P. Revol: CERN 99-11
http://ab-atb-eet.web.cern.ch/ab-atb-eet/Papers/TARC/tarc_nima.pdf

The ASTE project (JAERI, FZJ, PSI, ORNL, BNL collaboration) about mercury targets for neutron spallation was conducted on an AGS extraction line by Meigo et al. As a preliminary, it aimed at establishing the reliability of ICT measurements. ICT was compared to Cu foil activation and SEC (secondary electron emission) at 1.9, 12 and 24 GeV. Significant variations were reported for ICT vs. Cu activation at low energy. It is attributed to "uncertainty of activation cross section below 2 GeV." At higher energy, it shows "remarkably good agreement ... within 0.9%". Overall, Measurement of ... by Integrating Current Transformer... (ASTE) concludes that ICT uncertainty is <3%.
http://jolisf.tokai-sc.jaea.go.jp/pdf/dat/JAERI-Data-Code-2001-014.pdf

It is not surprising that large differences are observed vs. activation techniques. Activation techniques rely on cross sections which vary with energy, and signals from activation are themselves very small. On the other hand, ICT relies solely on the electric pulse electromagnetic field.

How short a pulse can be integrated by ICT has also been questioned. The agreement between ICT pulse measurement and total current has been amply demonstrated, in many labs, and it is used routinely to calculate the injection or extraction efficiency. It consists of summing ICT-measured pulses injected in a ring vs. the total current stored in the ring. This is done at almost every synchrotron in the world with pulses ranging from a few microseconds down to picoseconds. It produces meaningful reliable results. I don't know that such an exercise has been made with femto second pulses yet, but no pulse length dependance has ever been reported in the 1-million range from micros to picos. Dependance on particle type or polarity has not either been reported, from positrons or muons to fullerenes.

Problems have been reported with the use of ICTs. They fall broadly in 3 categories:
1) Charges from braemsstrahlung secondary emission, Compton electrons from high-energy photons, scattered ions, ionised gas, are collected by the ICT copper shield. Various parades have been tested successfully, e.g. deflecting electric or magnetic field, screen/collimator in front of ICT, etc.
2) A parasitic signal, coherent with the pulse, is picked up be the ICT output cable by electromagnetic coupling. The installation of common-mode chokes on the ICT output cable has often eliminated the parasitic signal. Sometimes, the parasitic signal and the ICT output pulse can be separated in time by increasing or shortening the ICT cable length.
3) Charges collected by the beam dump or target sometimes find a way into the ICT output cable braid; usually via a grounded feedthrough. Isolated (floating) feedthroughs and common-mode chokes can often eliminate the problem.

Troubleshooting. An effective manner of identifying a problem is to flip the ICT and compare its output signal before flipping and after flipping. If the signals before and after are the same but reverse polarity, it indicates the ICT output signal is solely due to charges passing through its aperture. When the signals before and after are different, it indicates that parasitic charges are collected by the ICT shield or cable.

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