Abstract
DC Current Transformers (DCCT) are widely used in the world of particle accelerators. Almost all circular accelerators have at least one DCCT installed in order to measure the circulating dc beam current.
The paper describes the principle and the evolution, from basic passive AC Current Transformers (ACCT) to sophisticated DCCTs. Additional features and auxiliary systems are also presented as well as magnetic materials used for the cores and for the shielding. Finally, some problems of integration, their possible solution and the performances currently achieved are addressed.

PRINCIPLE OF ACCTs
An AC Current Transformer (ACCT) consists of a coil wound around a core crossed by the particle beam to be measured, see Fig.1. A signal is generated in the secondary winding by a time varying magnetic flux due to the beam current.

Fig.1 ACCT schematic

Such a device has a low frequency response limited by the inductance of the secondary winding and by the load impedance, corresponding for practical cases to a few kilo Hertz. To overcome this limitation, an amplifier reducing the load impedance and feedback has been added [Ref.1, 2], allowing the extension of the low frequency cut-off to a few Hertz but still not to dc.

PRINCIPLE OF DCCT
The need to measure the dc current arose with the particle accumulators in which the coasted beam stays for days.
The principle of fluxgate magnetometer [Ref.3] has been applied to cover the missing frequency bandwidth of the ACCT [Ref 4, 5]. It resides in the utilization of a magnetic modulator exploiting the non-linear magnetization curve of soft ferromagnetic material. Two cores are fed in opposite phase with a current or a voltage signal according to the chosen configuration. The pair of cores must be carefully matched in order to minimize the induced signal after subtraction. In case of voltage excitation, the generator can be trimmed for each core by means of a balance. The Fig.2 shows the effect of a voltage modulation driving the cores into saturation. The frequency spectrum of the modulation current presents only odd harmonics when the BH curve is symmetrical with respect to the B and to the H axis; this is the case when the beam current is equal to zero. In contrary, a non-zero beam current causes an asymmetry of the BH curve and as a result the appearance of even harmonics and in particular of the second harmonic.

Fig. 2 Production of even harmonics

The magnetic modulator can be seen as a magnetic mixer shifting the beam signal frequency spectrum by twice the modulation frequency.
As seen above, the excitation generator can be either a voltage or a current generator, producing a rectangular, triangular or sinusoidal waveform. The choice of the modulation frequency depends on the magnetic material’s permeability variation with frequency, a few hundreds Hertz for crystalline material and a few kilo Hertz for amorphous materials. The essential features for a modulation generator are either high current or high voltage capabilities to saturate well enough.
the cores as well as frequency spectrum purity, the latter being not easy to achieve with highly non-linear load.

The extraction of the useful signal, the second harmonic, can be seen as the reverse operation of the frequency shift made by the magnetic modulator. Different options exist:

- synchronous detector
- resonant filter + detector or sample and hold
- detector of phase shift in saturation passages

The synchronous detector performs the product of the raw signal with a signal having the right phase and a frequency twice the modulation frequency.

The DCCT is often called zero-flux DCCT because of a feedback current cancelling the flux induced by the beam current. The aim is to increase the linearity range (to more than 6 decades) and to reduce the recovery time allowing the observation of low intensity beam after the passage of a high intensity one. The condition to achieve this goal is that the feedback current should be always equal to the beam current, therefore no interruption is allowed.

The frequency bandwidth of the magnetic modulator is limited to less than half the modulation frequency in order to avoid aliasing. Thus the signal induced in a third core is added to the dc signal to generate a common feedback. This additional part extends the high frequency cut-off of the overall transformer to some tens of kilo Hertz. The overall principle schematic is shown in Fig.3.

A demagnetization circuit insures the B-H curves to be well centred. The process avoids the memory effect and reduces the offset. This circuit should be activated, without any beam, at power on and on request.

Fig.3 DCCT general schematic

SIGNAL TREATMENT

Diverse signal treatments, performed either by hardware or software, can be applied to DCCT raw output signal.

- Ripple suppression, reduction of the modulation’s harmonics
- Base line restitution, acquisition of the perturbing signal for subsequent subtraction, only valid for accelerators with short cycle duration, a few seconds
- Offset suppression, acquisition of the DCCT signal in absence of beam then subtraction
- $\beta$ Normalization, transformation of the DCCT’s output signal proportional to the beam current into a signal proportional to the number of circulating charges

MAGNETIC MATERIAL

The magnetic material used for the dc core should be carefully chosen to gain the best sensitivity.

The criteria are the following:

- high magnetic permeability $\mu$ (>50000)
- low hysteresis losses, proportional to the area of the hysteresis curve
- low coercitive field, $H_c \sim 1\, \text{A/m}$
- Low eddy current losses, high electrical resistivity, lamination, strip-wound core, thickness of 10 to 50mm
- Low magnetostriction (change of physical dimensions when subjected to a magnetic field and conversely, source of noise)
• Minimum Barkhausen noise (related to magnetic domains structure and dimension)
• Good temperature stability

Three group of soft magnetic material are considered:
• crystalline, NiFe(Mo) alloy
• amorphous, TM alloy
• nanocrystalline, FeSIB alloy

INTEGRATION ISSUES AND POSSIBLE SOLUTIONS
DCCTs are sensitive to HF interferences due to RF systems and to beam structure, particularly to dense bunches. A good screening applied to the monitor, to the cables and to the boxes housing electronic prevent this effect. Capacitors disposed around the ceramic gap reduced the RF field emitted by the beam as well as the longitudinal impedance.

DCCTs are also susceptible to magnetic perturbations due to the surrounding equipment (dipoles, multipoles, power cables, power transformers, vacuum pumps, etc.). Magnetic shielding reduces these perturbations. The shielding effectiveness is improved by a multi layer configuration. The inner layers are made of high permeability material while the external one is made of high saturation material.

Radiation resistance of the front end electronic can be an issue for instruments placed in accelerators. The solution is to move away the electronics when possible, or to protect it with concrete and iron shielding. A wise choice of materials and components is recommended to insure the monitor perennity.

When heating the transformers during vacuum bake-out the core temperature should not exceed ~60ºC, a temperature far below the Curie temperature in order to avoid damage. A watercooling placed inside the DCCT around the bake-out jacket presents an efficient solution.

PERFORMANCES
Hereafter are listed the standard performances achieved by DCCTs.
• Full scale: any range from 10mA to 100A
• Resolution (S/N=1): typically 1 - 2µA (rms value for 1 s integration time)
• Frequency bandwidth: DC to ~ 50 kHz. Although often deliberately limited for noise reduction
• Temperature dependence: ~5µA/ºC
• Accuracy: ±500ppm + resolution, the main limitations being the calibrator and the monitor LF noise

CONCLUSIONS
The DCCTs are widely used; almost every circular accelerator has at least one device installed.

There is a demand to improve the performance in terms of resolution and stability i.e. reduction of the temperature dependence. Advancements are to be made to susceptibility to beam structure with high density bunches.

The test of new promising magnetic materials is not easy due to difficult procurement for small quantities.

Significant improvements are made in the domain of fluxgate magnetometer for space applications, can these progress benefit to DCCT [Ref.8]?

REFERENCES