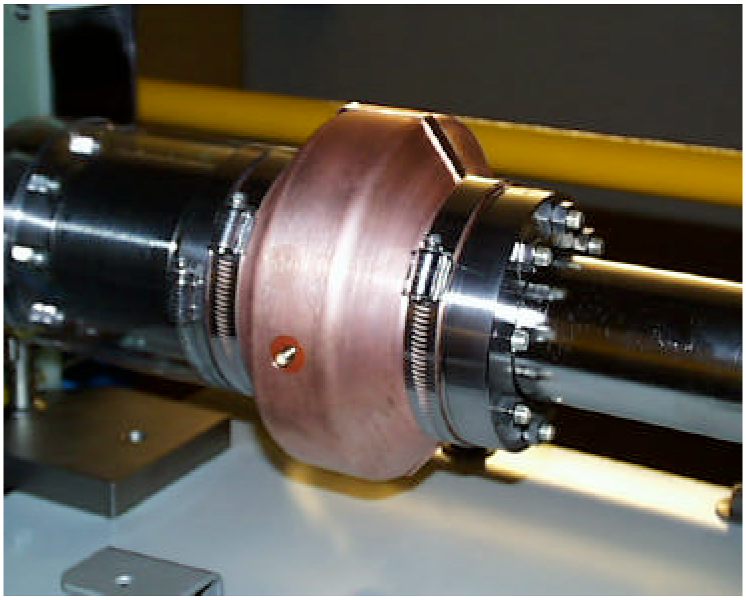
ALS Beam Instrumentation

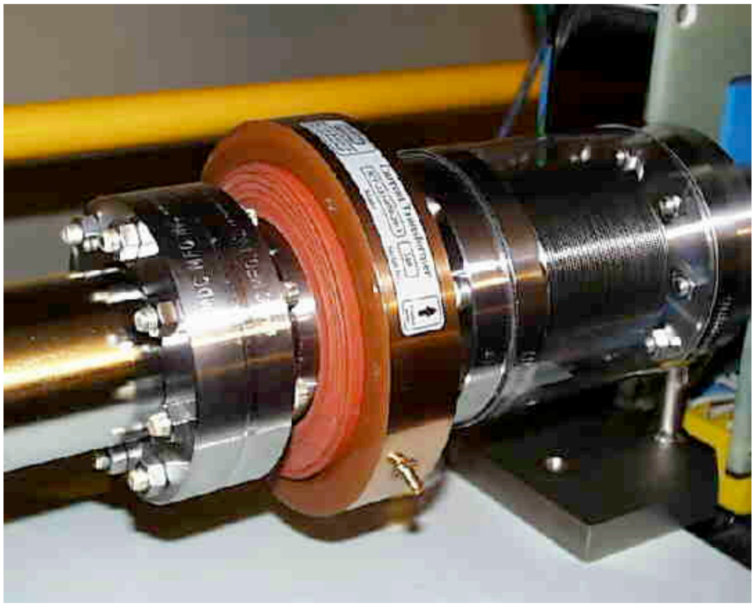
Beam Charge Monitoring

Jim Hinkson, July 1998

Introduction:
Beam charge monitors (BCM) are installed in several locations in the ALS beam injection systems. A complete BCM system consists of an integrating current transformer (ICT), cables, electronic integrators, and interface electronics to the control system. The BCMs measure charge in a beam bunch (or bunches) irrespective of bunch duration (from 1 ps to 2 ns). Sensitivity to beam position is small, less than 0.01 % / mm. Using data from the BCMs, we measure the efficiency of beam transport and acceleration from the exit of the linac to the entrance of the storage ring.



At this time there are five ICTs installed in the ALS and some additional units in the beam test facility (BTF). One ICT has been in operation at the exit of the linac for a number of years. During the May 1998 shutdown four more units were installed. One ICT is located in the LTB near the booster. Another one is located in the booster in straight section 3 (as shown in the photos). Two units are installed in the BTS, one at the booster beam extraction point and the other near the storage ring injection point. The photos show the ICT with and without its external shield in place.



Bunch Measurement:
The beam bunches in the ALS are very short, typically less than 100 ps (2σ). With an appropriate non-destructive beam sensor it is conceptually a fairly simple matter to measure the bunch current, integrate the resulting voltage pulse, and calculate beam charge. In practice this is difficult with short bunches.

A variety of devices may be used to measure beam charge. Q-electrodes (a simple ring encircling the beam), current transformers, striplines, and electrostatic pickups (buttons) are often used as the beam pickups. All of these devices have shortcomings when we measure very short bunches because bunch frequency components may extend well into the microwave region. It is very difficult if not impossible to construct a measurement system (pickups, vacuum feedthroughs, cables, and electronics) that can cope with the full frequency spectrum found in short bunches.

The ICT:

The problems with high frequency content in a beam bunch are overcome with the integrating current transformer (ICT) [1] which is the front-end transducer for the BCM. The ICT is expressly designed to measure bunch charge. Because it tends to integrate the bunch signal, temporal information about the bunch is lost.

Figure 1 illustrates the installation of an ICT in the ALS. The beam pipe is interrupted with a flanged ceramic gap from MDC. The ICT is installed around the ceramic gap and is supported by silicon rubber tape (not shown in the drawing but clearly seen in the second photograph) wound around the ceramic. Notice the arrow on the ICT in the photograph. It points in the direction of beam travel. In this arrangement the ICT produces a negative going voltage pulse in response to the electron beam bunch.

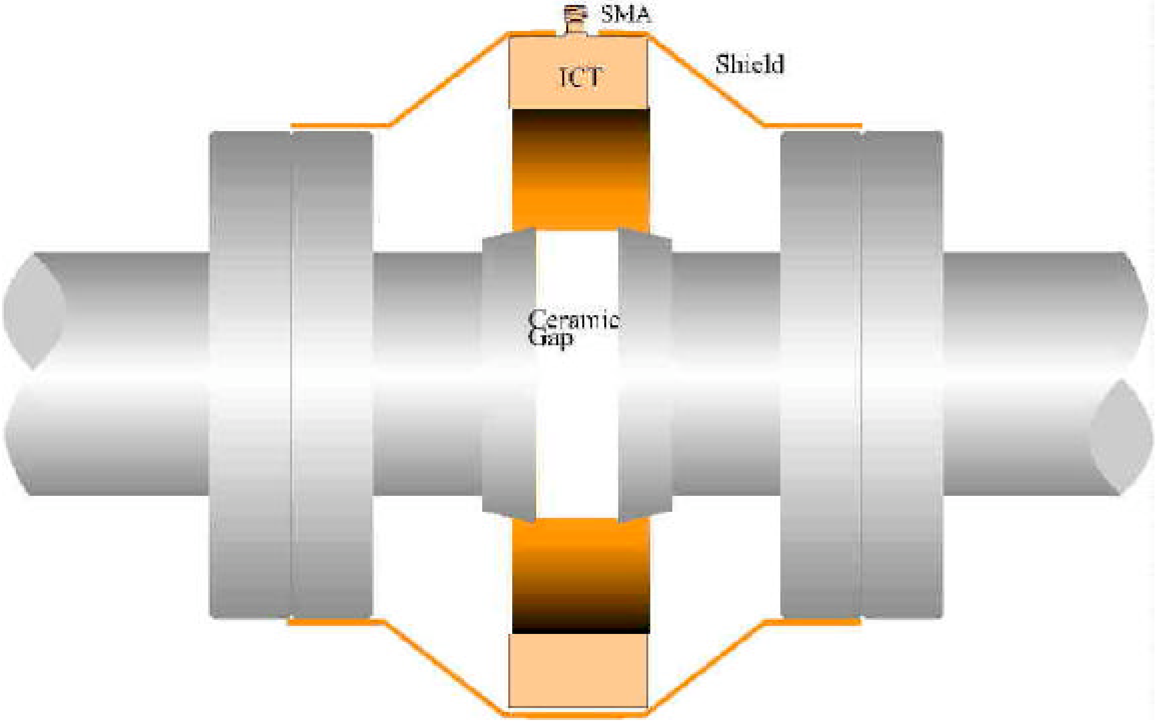


Figure 1. Drawing of ICT installation.

An over-all copper shield is placed around the ICT. It serves to protect the transformer, shunt unwanted beam-pipe currents around the core, and it prevents radiation of beam noise. The ICT itself is insulated from the shield with a thin plastic strip. A single hole in the over-all shield provides access to the ICT SMA coaxial connector. It is desired to have a single point ground in the system to minimize electrical noise in the measurement. This is the reason for isolating the transformer from the local ground.

How the ICT works:

Refer to figure 2. The ICT is fundamentally a current transformer having a tape-wound core of high-permeability metal alloy. The single primary turn is the beam. The ALS ICTs have 20 turns on the secondary winding. Exactly 1/20 of the beam current should flow in the secondary. By integrating the secondary current over the bunch duration we should measure exactly 1/20 of the beam charge.

No current transformer can respond faithfully to the full ALS bunch frequency spectrum. Core losses increase rapidly with frequency and eddy currents limit penetration of the magnetic field to a thin surface layer of the magnetic material. Additionally, at high frequency beam position dependence increases. Reducing the bunch frequency content before the magnetic core comes into play alleviates these problems. By shunting the primary circuit with low-inductance capacitors the beam current pulse is “integrated” thereby preventing the transformer core from “seeing” the beam’s high frequency magnetic fields. The integration capacitance is found in the ceramic gap and in the transformer. Approximately 40 chip capacitors are soldered across the small gap in the transformer electrostatic shield placing them in parallel with the primary. Additional capacitance is found across the secondary winding.

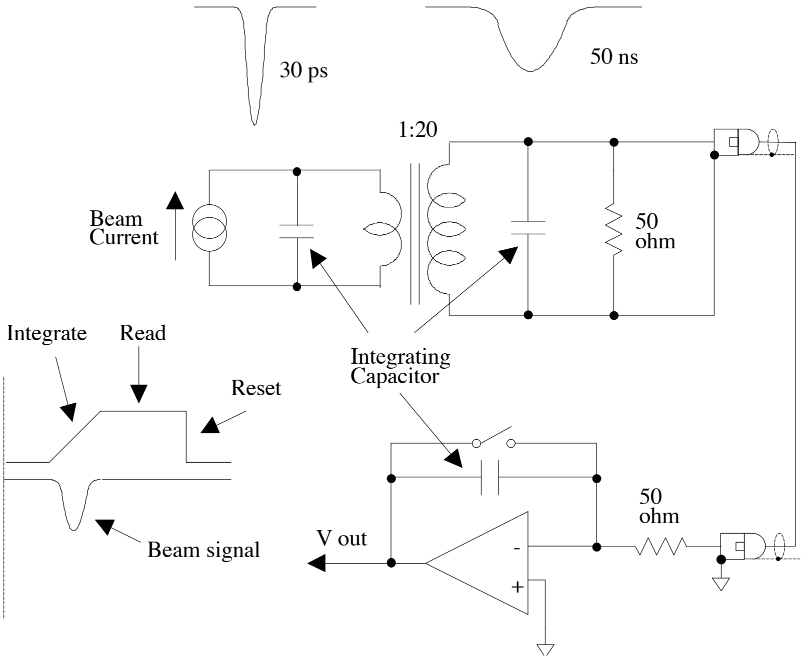


Figure 2. Simplified diagram of a BCM.

The charge stored in the integrating capacitors discharges into the transformer primary at a rate much slower than the beam di/dt. The transformer core is able to respond to the primary current, and with the 20 to 1 winding ratio, we obtain exactly 1/20 of the beam charge in the secondary circuit.

The secondary current flows in the internal 50 ohm resistor and in the external load resistance. If the external load resistance is 50 ohms, then one-half of the secondary current flows in it producing a voltage pulse with an area proportional to 1/40 beam charge. We integrate this pulse to obtain a DC voltage proportional to beam charge. This may be accomplished with a digital oscilloscope having an integration feature or with an electronic integrator. Using an oscilloscope with its input terminated in 50 ohms, beam charge is found from

$$Q_b = \int Vdt \cdot \frac{40}{50ohm}$$

where the integral of Vdt is volt-seconds in the pulse, 40 is the effective turns ratio, and 50 ohms is the load resistance. More simply, Q_b is 0.8 times the volt-seconds in the pulse.

If an electronic integrator is used, the charge in the pulse is stored in a capacitor. The amount of voltage across the capacitor is inversely proportional to its capacitance. After the voltage is scaled in an amplifier a sample and hold circuit is used to hold the voltage for reading by the control system.

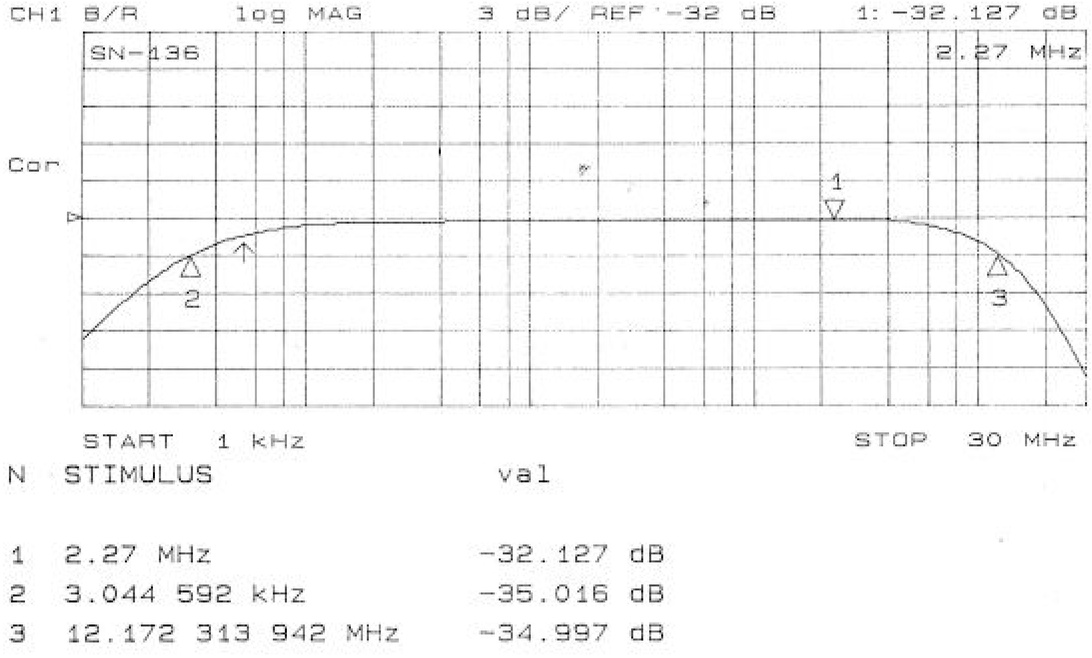
ICT Response:

The frequency response of an ICT is shown in figure 3. A single turn through the transformer forms the primary circuit. The primary wire is terminated in the 50 ohm R (reference) input of the network analyzer. The ICT output is measured in the 50 ohm “B” input of the analyzer. The measurement data show the ratio of B to the R input.

The markers on the ends of the response curve indicate the –3 dB or half-power points. The ICT response is similar to that of a bandpass filter. The –3 dB bandwidth is about 12 MHz. Marker 1 indicates the ICT response at 2.3 MHz. The response of the transformer at this point is –32.127 dB. We may find the transformer effective turns ratio from this number,

$$ratio = \left(10^{dB/20}\right)^{-1}$$

From this calculation we find the effective turns ratio is 40.4 to 1. We do not measure a 20 to 1 turns ratio because only one-half of the output signal power is measured in the network analyzer.


CH1 B/R log MAG 3 dB/ REF -32 dB 1: -32.127 dB

SN-136 2.27 MHz

Cor

START 1 kHz STOP 30 MHz

N	STIMULUS	val
1	2.27 MHz	-32.127 dB
2	3.044 592 kHz	-35.016 dB
3	12.172 313 942 MHz	-34.997 dB

Figure 3. Network analyzer measurement of ICT response.

The following graphs show raw and integrated signals from the ICTs. The data were not collected simultaneously, so they are not indicative of actual beam transport efficiency.

Figure 4 shows the typical response of the Linac ICT to 4-bunch beam. The peaks of four bunches are clearly seen at 8 ns intervals. The peaks are not observable with the other ICTs. This may be because the Linac ICT is older and of a different design, or it could be because the material used to support the other ICTs has a higher dielectric constant adding to the primary integrating capacitance. The smooth traces in the graphs are the integrated waveforms scaled in nano coulombs. Data integration was performed in an Excel spreadsheet with the 0.8 gain constant factored in.

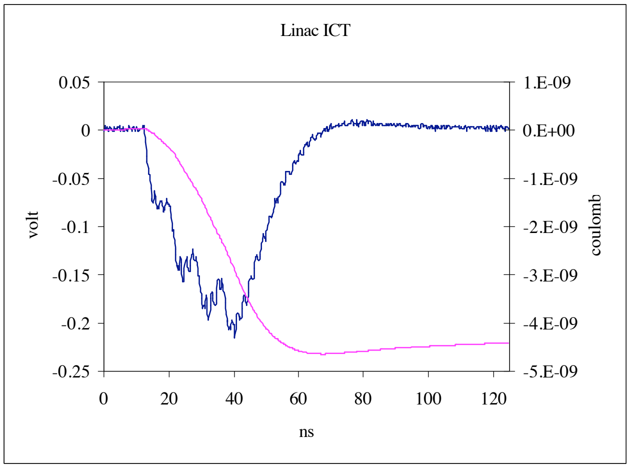


Figure 4. Linac ICT response to four bunches

Figure 5 shows the LTB ICT response to 4 beam bunches. Although attempts were made to eliminate noise, some interference from the booster injection kicker is seen in the data.

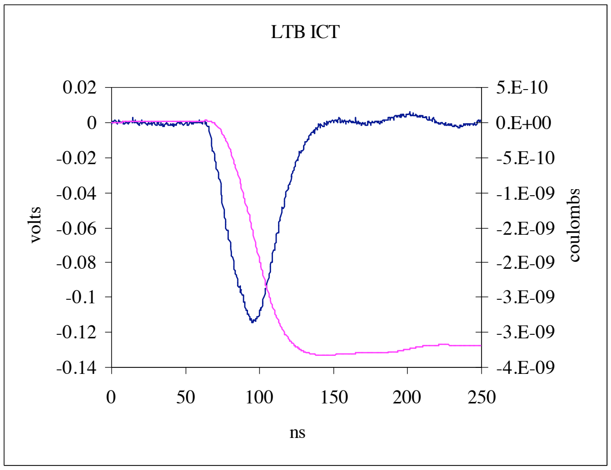


Figure 5. LTB ICT response to 4 bunches.

In figure 6 we can see booster beam injection. The first bunch contains 2.7 nC which when divided by the beam revolution time gives us the average current for that turn.

$$I_{avg} = Q_b / t_{rev} = 2.7nC / 250ns = 10.8mA$$

It can be seen in figure 6 that the beam bunch on the second turn has less charge than the first. Normally all the beam is captured in the booster and survives until beam instability causes some loss 100 to 200 μs after injection. Work is currently underway to improve booster acceleration efficiency.

Approximately 350 ms after beam is injected into the booster synchrotron it is extracted in a single turn. Figure 7 shows the final turns of the beam and before it is extracted. The four bunches contain about 1 nC total which is equivalent to 4 mA average current. Some noise from the extraction kicker is seen in the signal. Note that we see a pulse less than 40 mV peak for 1 nC. We may install pre amplifiers at the ICTs to increase the signal amplitude and improve the signal to noise ratio.

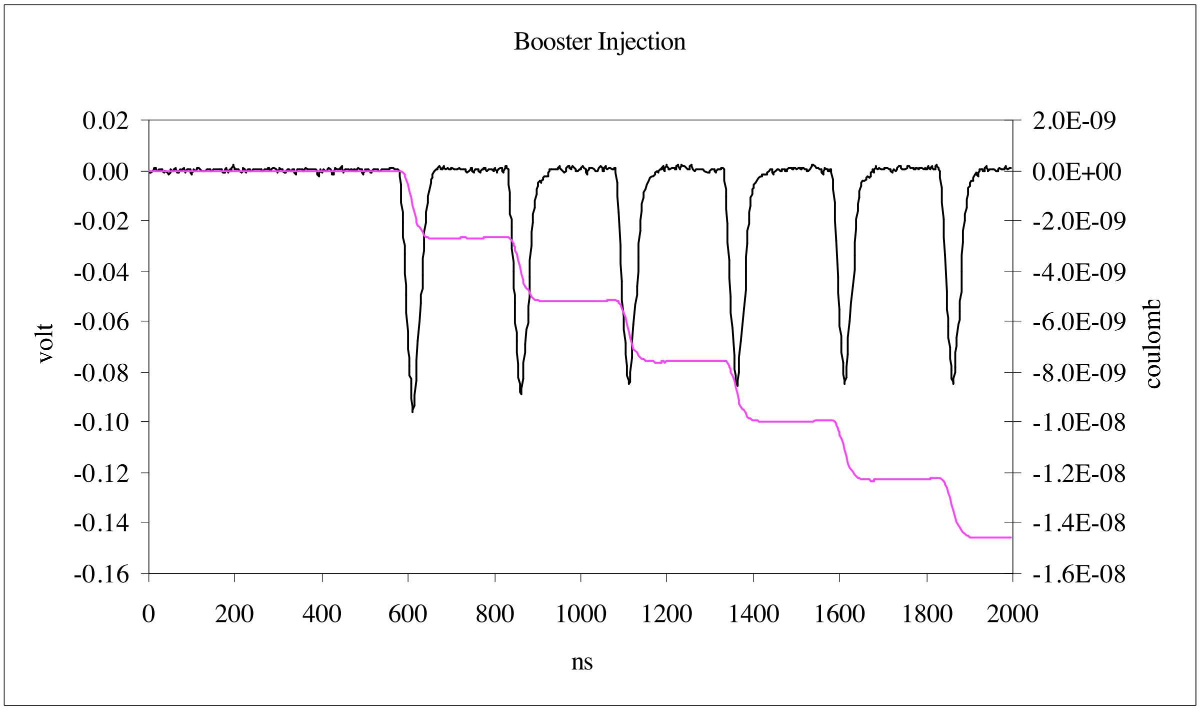


Figure 6. Six turns of booster beam at injection.

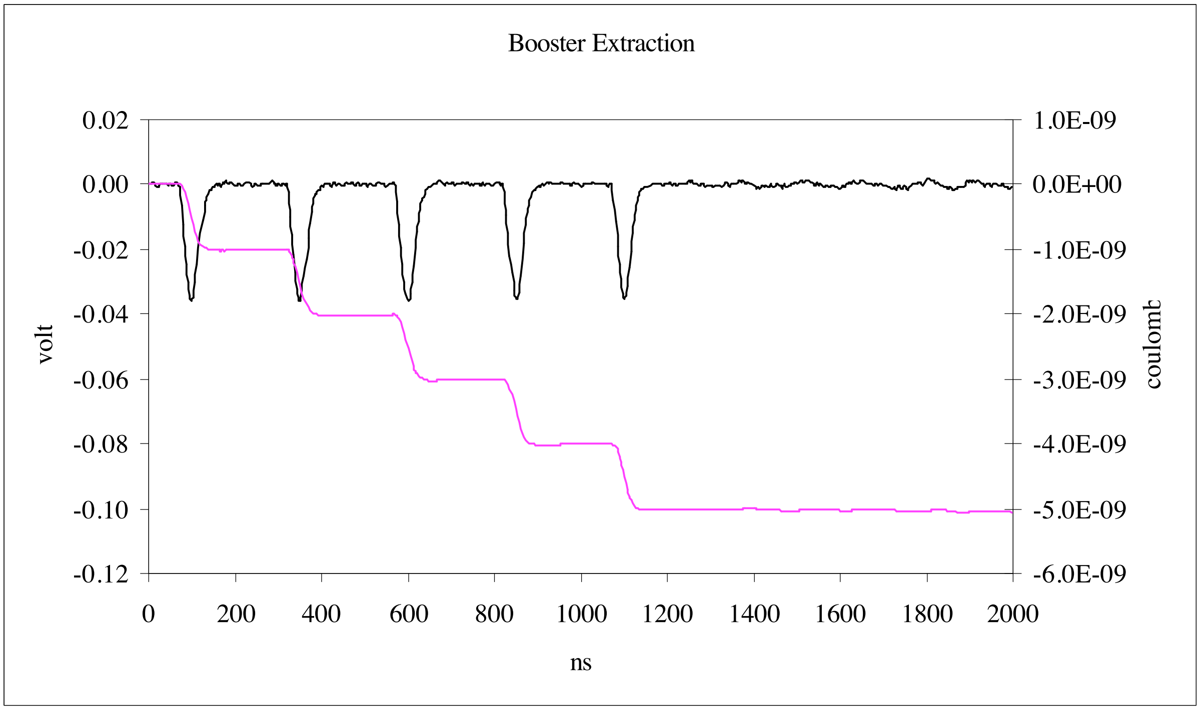


Figure 7. Booster beam at extraction.

Figure 8 shows the beam measured by the BTS ICT1 near the extraction point. The last bunch measured

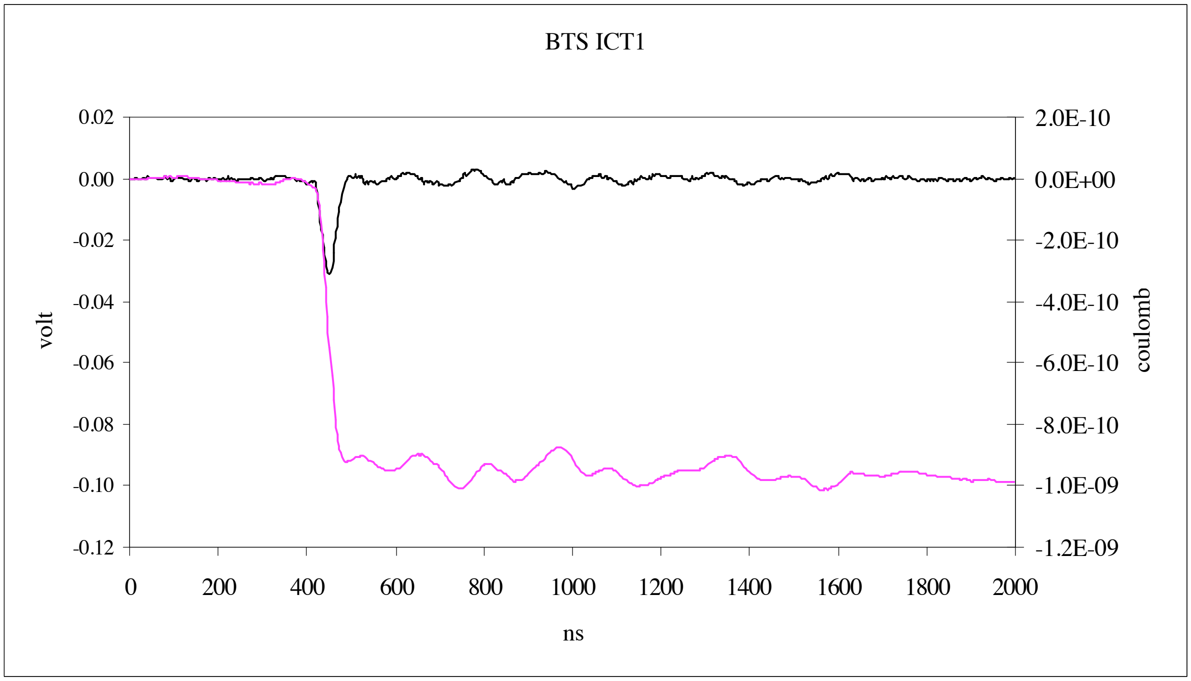


Figure 8. Booster extracted beam at BTS ICT1.

by the booster ICT has been compared with the bunch measured by the BTS ICT1. It appears that 100% of the booster beam is routinely extracted.

Figure 9 shows the beam that arrived at the injection point in the storage ring as measured by BTS ICT2. This graph is on a longer time scale to show interference from the storage ring bump magnets. Several measurements have shown that normally 100% of the beam is transported down the BTS. When these measurements were taken the charge injected into the storage ring was about 1 nC which is equivalent to 1.5 mA average current in the ring.

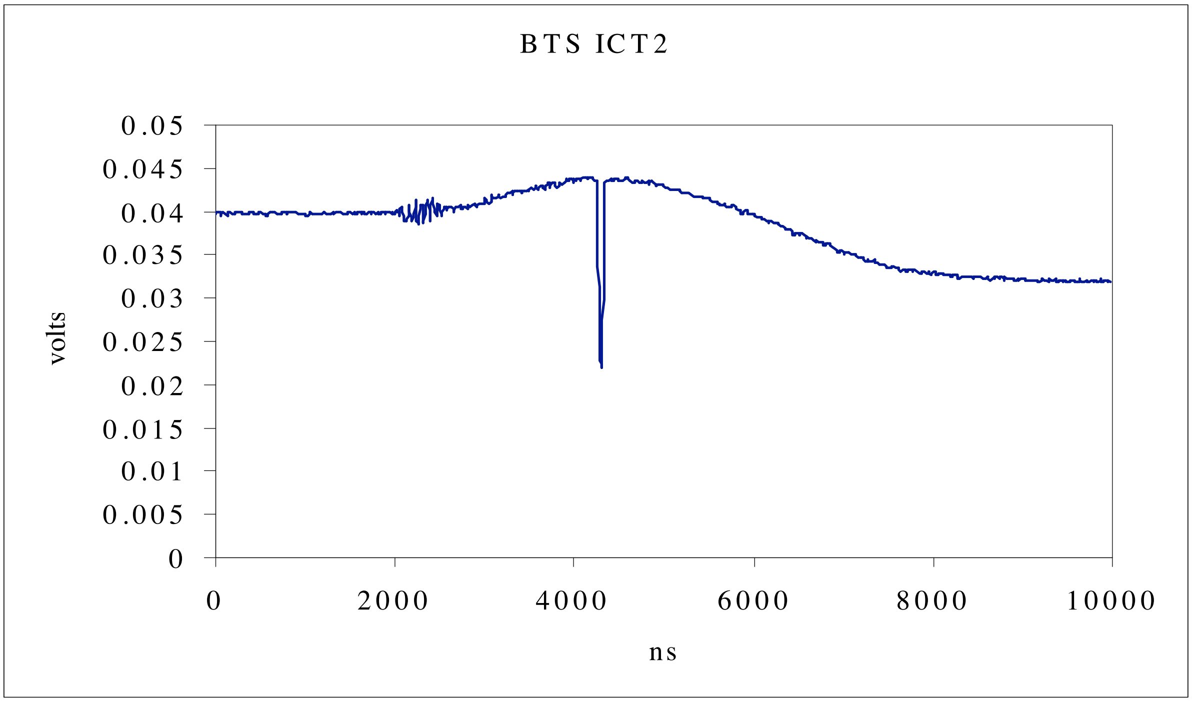


Figure 9. BTS ICT2 beam response. Bump magnet interference shows clearly.

Getting the data:
Signals from the ICTs are available for viewing on ALS oscilloscopes. Although the ICT signals are not a direct measurement of beam charge, they are useful for observation of relative amplitude, and the booster ICT signal is useful for viewing beam instability and turn-by-turn loss.

Electronic integrators convert the ICT signals into voltages proportional to charge. The conversion factor is 10 nC / volt. These voltages are read by the control system and are available in the ALS database.

The booster DCCT is normally used to measure average current during acceleration. Its analog bandwidth is DC to 1 kHz. The signal rise time is about 350 µs, which makes the DCCT useless for measurement of early beam loss. A fast-cycling integrator is used to convert the booster ICT signal into a voltage signal that is updated once per turn. This signal may be scaled to represent turn-by-turn current making the ICT useful for fast loss measurements on an oscilloscope. At the time the ICTs were commissioned we determined that 60% of the injected beam is typically lost in the first 200 µs.

Beam Current Measurement Basics

To understand how the ICT is able to measure beam current (charge) it may be appropriate to review a few basic aspects of beam current measurement by magnetic means.

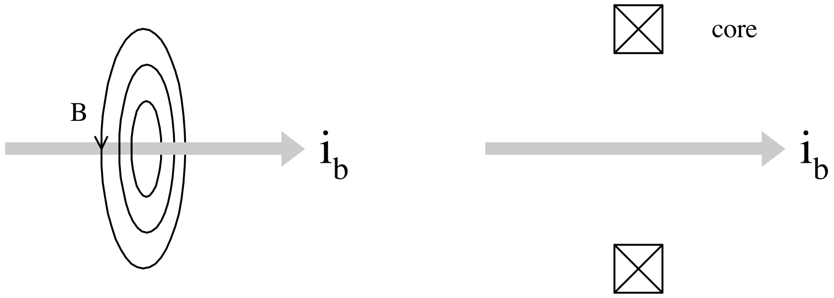
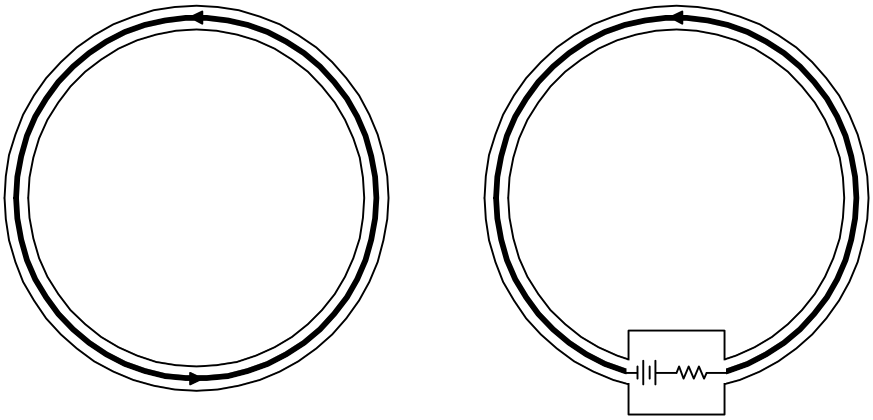


Figure 1. (a) Magnetic field surrounding a current-carrying conductor. (b) A magnetic core surrounding a particle beam.

A conductor carrying a current has about it a magnetic field as in figure 1a. It is the same with a beam of particles. If we place a magnetic core in the vicinity of the wire, flux is induced into the core. Figure 1b shows a ring (toroid) of magnetic material surrounding a beam.

Electrical engineers and technicians often make an analogy between beam in a metal pipe and current flowing in a coaxial cable. We know we cannot measure current flowing in the cable center conductor by magnetic measurements outside the cable shield if the shield forms the current return path. We can however measure beam current with magnetic field sensors outside a metal pipe. This apparent contradiction may be explained in figure 2.



(a) (b)

Figure 2. (a) A coaxial cable closed on itself. (b) A coaxial cable current flowing in the center conductor only.

Imagine in figure 2a we have launched a pulse of current into the coaxial cable and then closed it upon itself. A voltage exists between the center conductor and the shield. We know that magnetic fields produced by current flowing in the cable center conductor are counteracted by magnetic fields created from current flowing in the cable outer shield in the opposite direction. An external magnetic field sensor will not "see" the pulsed current.

In 2b we have a different situation. The current or "beam" is flowing in the cable center conductor only. We do not have counteracting magnetic fields produced by current in the shield. A magnetic monitor outside the shield would "see" the flowing current. This situation is similar to the condition we have in an accelerator.

It is usually impractical to install the magnetic core in inside the beam pipe, so the core is placed on the outside as in figure 3a. High frequency magnetic fields from the beam do not penetrate a metal beam pipe because of the skin effect. At sufficiently high frequency where skin depth is a fraction of the wall thickness, attenuation of the beam magnetic fields external to the beam pipe is effectively complete.

A magnetic core on the outside of a metal beam pipe may not only couple to beam fields but also to fields produced by other currents flowing in the pipe. This is especially true in accelerators having pulsed or ramped magnets. Our purpose is to measure beam current (or charge) and to exclude other currents that may actually be larger. It is principally for this reason that we install an insulating gap in the beam pipe. The gap prevents non-beam current from flowing through the core, and it permits higher frequency components of the beam to reach the core. Figure 3b shows a ceramic gap and an over-all outer shield installed in the beam pipe. The main function for this shield is to provide a path for the unwanted currents. Another important reason for installing an over-all metal shield is to prevent radiation of electromagnetic noise generated by the beam.

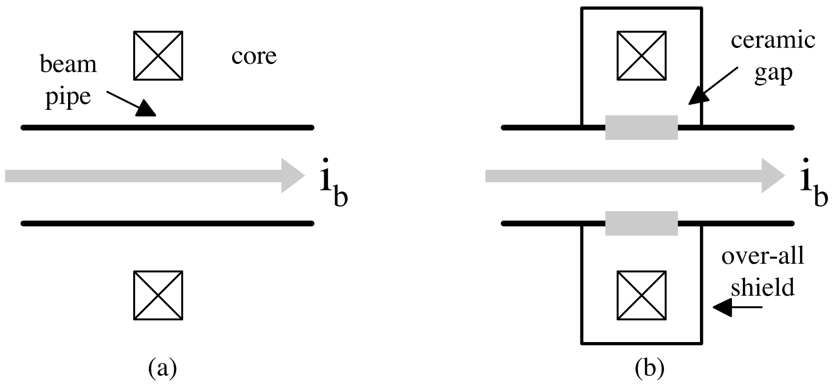


Figure 3 (a) Core surrounding a beam pipe. (b) Core with ceramic gap and shield.

Having installed an over-all shield over a break in the beam pipe means we have constructed a cavity that will probably be driven into resonance by the beam. This is not important in the LBT, BTS or in the booster where the average beam current is low. It would be quite important in the storage ring. The high-current, short-bunch beam in the storage ring would excite many resonance modes in the cavity and possibly destroy the ICT. Also, the cavity would create unwanted beam impedance. Successful installation of a current transformer in the storage ring would not a simple matter.