Signal Estimates and Electronics Scheme for Fast Current Transformers in High-Energy Transfer Lines

A. Reiter, H. Reeg
Beam Instrumentation Department

August 19, 2016

1 Introduction

Signals levels for a fast current transformer (FCT) in the high-energy transfer lines are calculated for an electronics chain consisting of switchable attenuator/amplifier unit, coaxial transmission line, and ADC data acquisition system. The estimate response to a single pulse are compared to measured data to verify the model calculation.
On the basis of maximum expected bunch charges at FAIR, some suggestions are made concerning the parameters of the readout electronics. The detection limit at the low-intensity is briefly explored for one measurement of signal-to-noise ratio S/N∼3.

2 Beam and Transformer Parameters

2.1 Beam Parameters

High-intensity beam pulses of 2.5x10^{13} protons and 1x10^{12} U^{+28} have been assumed with a total length of 50 ns. For a single pulse of triangular shape the corresponding peak currents are 80 A and 100 A, respectively.

2.2 Transformer Sensitivity

Commercial fast current transformers, e.g. by Bergoz, are available in a range of sensitivities S between 0.5 to 20 V/A, depending on the winding ratio. In this document we assume $S = 0.5$ V/A as the peak current may reach 100 A for the shortest bunches. Two such FCT models have been purchased:

- FCT-220-0.50V/A-LD-H: low-droop (LD), rad-hard (H), 700 MHz bandwidth, rise time = 0.5 ns, droop = 0.06%/μs
- FCT-220-0.50V/A-LLS-H: low-lateral sensitivity (LLS), rad-hard (H), 237 MHz bandwidth, rise time = 1.5 ns, droop = 0.06%/μs

The latter type of low-lateral sensitivity has been installed in the HTP beam line in 2016. This model is foreseen for the high-energy transfer lines of the FAIR facility, while the high-bandwidth model may serve for dedicated beam structure investigations in ring machines.

2.3 Electronics Chain

The electronics chain for the transformer installed in the beam line HTP after synchroton SIS18 is composed of:

- Sensor: FCT-220-0.50V/A-LLS-H
- Front-end hardware: remote-controlled attenuator/amplifier stage
- Signal transmission: coaxial cable (90 m RG 213, <4 m RG 174/RG58)
- Aquisition hardware: Struck ADC SIS3305, 1.25 GSa/s, BW = 2 GHz, 10 bits

An overview of the key components is given in table 1. A similar scheme, illustrated in Figure 1, will be a likely implementation for the new FAIR facility. Some parameters like amplifier gains, ADC sampling rate or number of bits are still to be defined.

2.4 Noise Figure & ADC Resolution & Dynamic Range

We consider a signal acquisition in an ADC with following parameters: symmetric ± 1 Volt input range, fixed centered baseline and 10/12 nominal bits. The ADC granularity is then $\sim$2.0/0.5 (mV/channel). If we select a 12 bit ADC and assume 10 effective bits, its dynamic range is 62 dB for the symmetric voltage input range. For unipolar pulses the dynamic range is reduced to 56 dB as one effective bit is lost.
A 10 bit ADC does not provide sufficient resolution, since the output noise of the 45 dB amplifier is 2.1 mV(rms), equivalent to 1 ADC channel. For a 20 dB amplifier the noise voltage is accordingly smaller. Hence, a 12 or 14 bit ADC seems the better choice. [1]

3 Signal Estimates & Comparison to Data

3.1 Case 1: Detection Limit

In table 2 we calculate the signal amplitude for a 10 pC pulse of 100 ns total length and triangular shape. The resulting 0.2 mA peak current produces an output voltage of 0.1 mV. Amplified to about 15 mV this corresponds to a digitized level of about 8 channels in a 10 bit ADC. This estimate is in good agreement with the measured signal of Figure 2. The average peak charge is 7.2 pC in the four 75 ns long pulses.
If we regard the measured signal as detection limit, the charge of 10 pC in 100 ns corresponds to 6.5x10^7 (or $\sim$1x10^8) protons for the present exerimental setup. This seems to be a reasonable limit and, thus, gains >45 dB are not required.

[1] If the trace is to be integrated to recover the bunch charge, the reader is referred to reference [3] which demonstrates how the quality of results can improve between an 8 and 12 bit digitizer.

Table 1: Some important parameters of attenuator and amplifier model. Information on an alternative transmission via an optical link has been added for comparison. For definitions of MDR, DR, SFDR see ref. [1, 2].

	Attenuator	Amplifier	Optical Link
Model	MTS T-PAS-1000/63-5401	Miteq AU-1423	point2point PAT-K1-6H + PAR–K1-6R
Bandwidth [MHz]	DC - 1000	0.3 - 500	0.002 - 1350
Insertion loss [dB]	-(2–3)	0	-(1–3)
Att./gain [dB]	-63 – 0	45.2	0
Step accuracy [dB]	± 0.3		
Comp. point [dB]	—	11	>0
V(pp) [mV]	—	2244	632
Input P3 [dBm]	—	$\sim$(11+10)	>10
Noise figure	—	1.15	24
Equiv. RMS input noise [mV]	—	0.011	0.26 (1300 MHz) 0.16 (500 MHz)
RMS output noise [mV]	—	2.1	0.26
Minimum Discernible Signal MDS [dBm]	—	-85.9	-58.9
Dynamic Range DR [dB]	—	97.9	57.9
Spourious Rree Dyn. Range SFDR [dB]	—	71.1	39.3

3.2 Case 2: High-Intensity Limit

Signal estimates for high-intensity proton and Uranium beams have been summarised for 50 ns pulses in Figure 4. Output voltages from an attenuator/+40 dB amplifier chain have been calculated for a triangular signal. The last column states the signal level in units of ADC full scale.
For a typical ADC of ±1 Volt input the maximum attenuation of -20 dB (= -60 dB attenuator + 40 dB amplifier) is not sufficient at the upper intensity limit; the voltage exceeds the ADC range by a factor 8. To fit the maximum output voltage of 90 Volt into the ADC range an attenuation of -40 dB is required. Therefore, an additional path of +20 dB amplification must be added to cope with the expected dynamic range.

Table 2: Signal estimate for a 100 ns long pulse of 10 pC charge

Beam Parameters		
No. of particles	N_ion	6.50E+07
Charge of ions	q_ion	1
No. Of protons		6.50E+07
Total charge	Q_tot	10.4 pC
Pulse length of 1 bunch	tau_bunch	100 ns
No. of triangular bunches	n_bunch (h)	1
Charge per bunch	Q_bunch	10.4 pC
Protons per bunch		6.50E+07
Mean current in bunch	I_mean	0.10 mA
		104.1 μA
Peak current in bunch	I_peak	0.21 mA
		208.2 μA

Technical Parameters		
Sensitivity of FCT	S_FCT	0.5 V/A
Mean output voltage	U_mean	0.05 mV
		52.1 μV
Peak output voltage	U_peak	0.10 mV
		104.1 μV
total gain	gain_dB	43.5 dB
(ampl./att./cable)	gain	149.6
ADC input range	V_ADC	2.0 V
Nominal ADC bits	N_bit	10
No. Of ADC channels	N_ADC	1024 channel
Sensitivity (ch./V)	S_ADC	512 ch./V
Sensitivity (V/ch.)		1.95 mV/ch.
Mean ADC ouput	U_ADC_mean	4.0 ch.
Peak ADC output	U_ADC_peak	8.0 ch.

4 Conclusions

On the basis of the present estimates and measured response a few suggestions for the acqisition electronics are made:

- ADC: 1.0–1.5 GSa/s per channel, 12/14 nominal bits, input range ±1 Volt
- Attenuator stage: Signal level adjustment to amplifier input. Should also protect amplifier input, e.g. full attenuation, when switched off. The MTS T-PAS module has worked fine fo far and should be kept.
- Amplifier stage: Internal input protection (, e.g. fast clipping diodes) required. Output level must be matched to ADC input range. Suggested gains: +20 (model to be defined) /+45 dB (Miteq AU-1423 or equivalent)
- Signal bypass: A direct connection of the FCT signal to the ADC should be available via a bypass. The path is selected by active relays (relay off = attenuator/amplifier path selected).

The suggestions are illustrated in Figure 4. The dynamics covered by the three signal paths is [-45, +45] dB. The remote control requires a total of 8 lanes for attenuator (6), bypass (1), and amplifiers +20/+45 dB (1).

References

[1] "Receiver Dynamics", Cryptologic Quartlerly, Vol. 15, No. 4, National Security Agency, Winter 1996, USA
Definitions on amplifier parameters may also be found in catalogues of Trontech

[2] Rhode & Schwarz, *dB or not dB?*, Application Note 1MA98, October 2010

[3] M. Krupa et M. Gasior, "Precise Digital Integration of Fast Analogue Signals using a 12-bit Oscilloscope", WEPF18, IBIC2014, Monterey, CA, USA

List of Figures

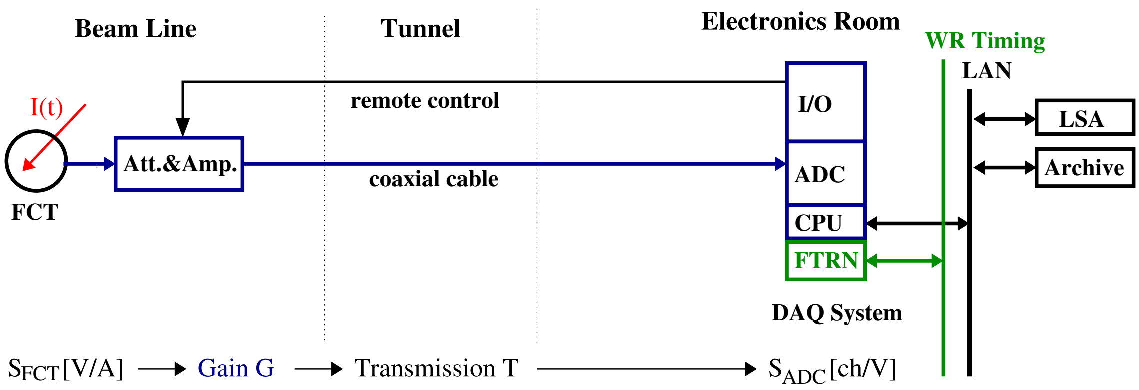

Figure 1: Sketch of data acquisition system. The FCT signal is fed to a front-end hardware consisting of remote-controlled attenuator and amplifier stage. The output is acquired in a sampling ADC after transmission to the electronics room via a coaxial cable.

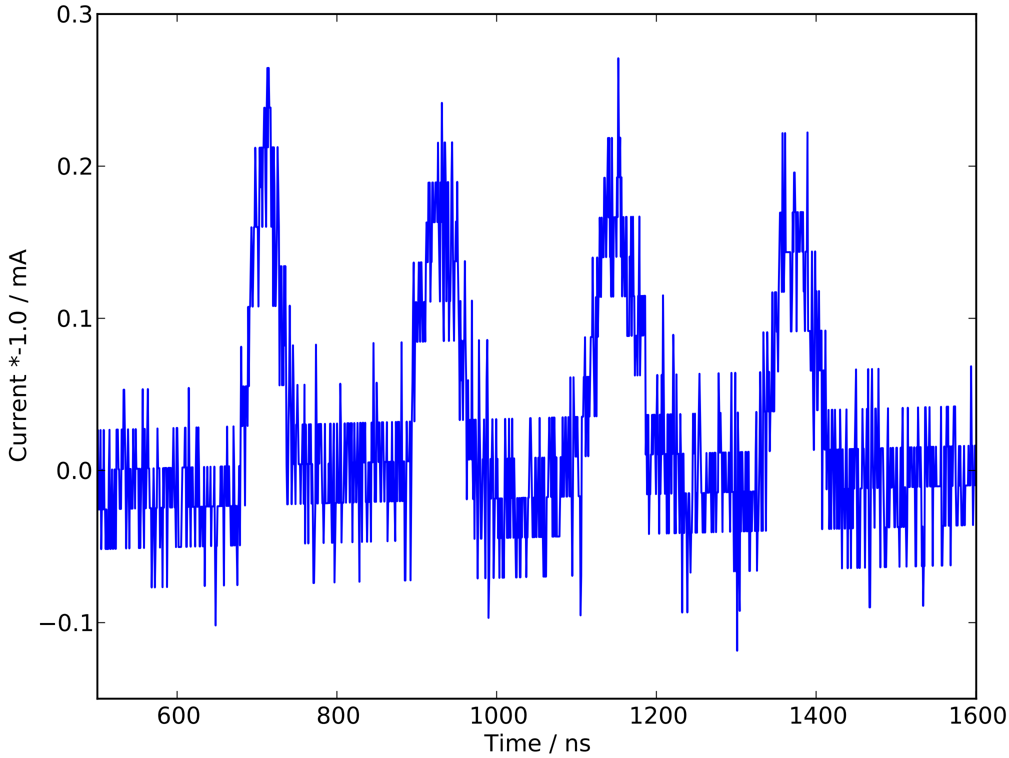

Figure 2: Minimum detectable signal (S/N$\sim$3) for the transformer FCT-220-0.50V/A-LLS-H in the HTP beam line. Average charge per pulse$\sim$7.2 pC; total pulse length$\sim$75 ns, peak amplitude 8-10 ADC channels.

Sensitivity $0,50 V/A Gain= 40,0 dB

Ion Type	Calculation of signal in Fast Current Transformer										
	Part. No	Charge	Pulse length (s)	Peak current (A)	Mean voltage (V)	Voltage attenuator (dB)	Switch-able att. output (V)	Attenuation (dB)	Switch-able att. output (V)	Amplifier (V)	ADC (Vmax< 1V) % FS
Protons	2,50E+13	1	5,00E-08	1,60E+02	8,0E+01	-60	8,0E-02	-1,00	7,1E-02	7,1E+00	713,0
	2,50E+12	1	5,00E-08	1,60E+01	8,0E+00	-60	8,0E-03	-1,00	7,1E-03	7,1E-01	71,3
	2,50E+11	1	5,00E-08	1,60E+00	8,0E-01	-40	8,0E-03	-1,00	7,1E-03	7,1E-01	71,3
	1,00E+10	1	5,00E-08	6,40E-02	3,2E-02	-10	1,0E-02	-1,00	9,0E-03	9,0E-01	90,2
	1,00E+09	1	5,00E-08	6,40E-03	3,2E-03	0	3,2E-03	-1,00	2,9E-03	2,9E-01	28,5
	1,00E+08	1	5,00E-08	6,40E-04	3,2E-04	0	3,2E-04	-1,00	2,9E-04	2,9E-02	2,9
Uranium	1,00E+12	28	5,00E-08	1,79E+02	9,0E+01	-60	9,0E-02	-1,00	8,0E-02	8,0E+00	798,6
	1,00E+11	28	5,00E-08	1,79E+01	9,0E+00	-60	9,0E-03	-1,00	8,0E-03	8,0E-01	79,9
	1,00E+10	28	5,00E-08	1,79E+00	9,0E-01	-40	9,0E-03	-1,00	8,0E-03	8,0E-01	79,9
	1,00E+08	28	5,00E-08	1,79E-02	9,0E-03	0	9,0E-03	-1,00	8,0E-03	8,0E-01	79,9
	1,00E+06	28	5,00E-08	1,79E-04	9,0E-05	0	9,0E-05	-1,00	8,0E-05	8,0E-03	0,8

Figure 3: Signal estimates for high-intensity proton and Uranium beams. Output voltages from an attenuator/40 dB amplifier chain has been calculated for a triangular signal of 50 ns total lentgh.

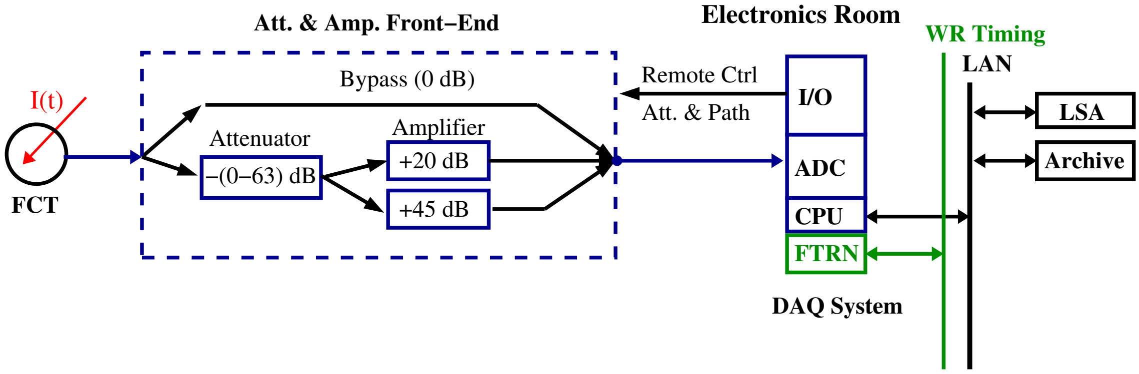

Figure 4: Suggested signal paths for a front-end hardware of a FCT with 0.5 V/A sensitivity. The front-end dynamic range covers [-40,+ 45] dB with a suitable granularity for a ± 1 Volt ADC input.