

Toroid Beam Current and Intensity Measurement Requirements in the Linac

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Fernanda Garcia, Craig Drennan

1. Scope of the Project

The scope of the Linac toroid measurement upgrade includes new hardware and front-end processing software for the measurement and processing of the Linac beam pulse current and intensity. Beam current, in coulombs per second (Amperes) or particles per second, is sampled over the entire Linac beam pulse. This data is processed and delivered for plotting and other ACNET applications, and is used for accelerator commissioning, monitoring and diagnostics.

Beam pulse intensity is a single value computed for each Linac pulse. These particles per pulse measurements are used by the Beam Budget Monitor. The Linac Beam Budget is monitored by Accelerator Division Operations Department to guide Main Control Room (MCR) on the amount of beam delivered to the experiments. This toll was created exclusive for Operators monitor purpose.

AD/Operations Department is not responsible for the accuracy and calibration of any of the toroids that they monitor. There are 3 warning limits: the lowest limit is known as "*Mau's limit*" or "*MCR's limit*", the middle limit and the highest represents the maximum allowed protons per hour delivered to a particular enclosure based on the Safety Assessment Document (SAD) for that particular enclosure.

The Linac will continue to use the existing toroids in the Linac beam line except for a new, large aperture toroid at the momentum dump and three new toroids that will be installed in the 750KeV area for the new RFQ. The current NIM module amplifiers and integrators will be replaced by a simple pre-amplifier and a high speed, FPGA based digitizer with VME standard data transfer to a power PC front-end processor.

2. Linac Beam Current/Intensity Specifications

Parameter	Minimum	Typical	Maximum
Linac Pulse Repetition Rate			15Hz
Beam Intensity, Particles per Pulse		5.10E+12	2.13E+13
Beam Current Measurement Range	5 mA	34 mA +/- 1 mA	60 mA
Beam Pulse Duration (width)	1 usec	25 usec	100 usec
Beam Current Record Sample Rate	10 MHz		
Beam Current Measurement Rise Time (within 2%)			200 nsec
Beam Current Modulation BW	3 MHz		
Beam Current Resolution (Note 2)	0.1 mA		

Note 1: Typical values are based on Intensity Frontier Programs.

Note 2: The maximum 60 mA for beam current and 80-100 usec beam pulse width are estimates for MTA beam demand. Not Intensity Frontier expectations. How often MTA will runs will depend on Laboratory Program Planning.

See Appendix A for a list of Linac Toroids.

3. Linac Beam Intensity and the Beam Budget Monitor Specifications

An integrated, summed accumulation, of the beam current measurements is to be made. This accumulated value at the end of the data acquisition interval is used to compute the pulse intensity, the particles per pulse. This is determined by

$$\text{Beam Current Sample (Amps)} = \frac{\text{Data Value (Bits)}}{\text{Toroid Gain} \left(\frac{\text{Volt}}{\text{Amp}} \right) * \text{Digitizer Conversion} \left(\frac{\text{Bits}}{\text{Volt}} \right)}$$

Beam Intensity (Particles per Pulse) =

$$\frac{\text{Data Sample Rate (Sec)}}{\text{Charge per Proton} \left(\frac{\text{Coulombs}}{\text{Particle}} \right)} * \sum_{\text{All Samples}} \text{Beam Current Sample} \left(\frac{\text{Coulombs}}{\text{Sec}} \right)$$

The Beam Current Samples can be summed either on the digitizer module and the result transferred to the front-end processor along with the beam current samples at the end of the data acquisition interval, or the sum can be computed in the front-end processor. The other scale factors are typically applied in the ACNET applications and devices that use these values.

3.1 Linac Beam Budget Monitor

The main application that requires beam intensity, particles per pulse, measurements is the Linac Beam Budget Monitor. The BBM is a meter that provides a count of the particles accelerated through different beam lines around the Lab including the Linac. The ACNET application D105 "Beam Budget Monitor" is currently maintained by Bill Marsh. The Front-End application that D105 accesses was originally written by Bob Goodwin and is described in his note "Beam Summing", June 17, 1994. This note is available at

http://www-inteng.fnal.gov/Integrated_Eng/GoodwinDocs/pdf/LA%20docs/Beam%20Summing.pdf

It has also been copied in Appendix B of this document.

3.2 Linac Limits on Accelerated Particles

Parameter	Minimum	Typical	Maximum
Linac Pulse Repetition Rate, Hz			15
Linac Particles per Pulse, ppp		5.10E+12	2.13E+13
Linac Particles per Second, pps		7.65E+13	3.19E+14
Linac Particles per Hour, pph		2.75E+17	1.15E+18
Linac Peak Beam Power, kW (Reference: 66.667 ms interval)	0.20	4.90	20.40
Linac Peak Beam Energy, kJ	0.01	0.33	1.36

Note: The above parameters implicitly consider the pulse repetition rate of 15 Hz. For instance the particle per second value is equal to Particle per pulse times 15 pulses per second, and the Linac Beam Energy in kilo-Joules is 1/15 the Linac Beam Power in kilo-Watts.

3.3 Program Specific Linac Parameters

LINAC PARAMETERS	Intensity Frontier Program	NTF	MTA		Studies		Units
Linac Peak Current	34.00	34.00	34.00		34.00		mA
			Min	Max	Min	Max	
Pulse Repetition Rate	15.00	15.00	15.00	15.00	15.00	15.00	Hz
Beam Width	24.00	64.00	1.00	100.00	1.00	100.00	usec
Particles per pulse	5.10E+12	1.36E+13	2.13E+11	2.13E+13	2.13E+11	2.13E+13	ppp
Particles per second	7.65E+13	2.04E+14	3.19E+12	3.19E+14	3.19E+12	3.19E+14	pps
Particles per hour	2.75E+17	7.34E+17	1.15E+16	1.15E+18	1.15E+16	1.15E+18	pph
Peak Beam Power	4.90	13.06	0.20	20.40	0.20	20.40	kW
Peak Beam Power	0.33	0.87	0.01	1.36	0.01	1.36	kJ

Additional Notes:

1. Linac already runs at and will deliver 15Hz Beam to Booster for Intensity Frontier
2. For each Beam pulse sent to Booster, 2 usec goes to the Momentum Dump area.
3. RFQ source is expected to be capable of 100 usec long beam pulse.

Intensity Frontier Program will most likely be the dominant mode that Linac will run.

Appendix A: List of Linac Toroid Beam Current Monitors

Linac Toroid Beam Current Monitors

Information from
A. Ibrahim, 9/12/2011

ACNET Name	Instrumentation Location
L:HTOR1	Discontinued
L:HTOR2	
L:HTOR3	
L:HTOR4	LIU-000
L:HTOR5	
L:HTOR6	
L:HTOR7	Discontinued
L:HTOR8	
L:HTOR9	
L:ITOR1	
L:IHTOR2	LIG-100 / LE1-RR4-1
L:IHTOR3	
L:TO1IN	
L:TO1OUT	Discontinued
L:TO2IN	LE2-RR4-2
L:TO2OUT	
L:TO3IN	LE3-RR3-2
L:TO3OUT	
L:TO4IN	LIG-100 / LE4-RR3-4
L:TO4OUT	
L:TO5IN	Discontinued
L:TO5OUT	LE5-RR3-2
L:D0TOR	LIG-109
L:D1TOR	
L:D2TOR	
L:D3TOR	
L:D4TOR	
L:D5TOR	
L:D6TOR	
L:D7TOR	
L:D73TOR	LIG-1-- / LE8-RR2-2
L:TORSI	BGW-100 / LG1-RR3-3
L:TORSO	
L:TORMD	
L:TORSO	

Appendix B: Beam Summing Local Application

Beam Summing

Local application

Fri, Jun 17, 1994

For monitoring long term accumulations of raw data such as beam charge, it is necessary to do the pulse-by-pulse summing locally, then making the accumulations available to any host system. This note describes an implementation for this as a local application.

Parameters layout:

```
ENABLE B<00C4> BSUM ENABLE
BEAM B<009F> NO BEAM STATUS
OUTADDR <2F00>
CHAN1 C<001B> BEAM ACCUM TEST
CHAN2 C<0000>
CHAN3 C<0000>
CHAN4 C<0000>
```

The ENABLE Bit# enables operation of the BSUM local application. The BEAM status Bit# indicates what bit signals the presence of a scheduled beam pulse of the type summed by this application. The “beam” state is the sign bit of this parameter. The OUTADDR parameter is a 16-bit address in low memory where the output results are written. This address should be in an area that is zeroed at system reset time, in order to start the accumulations at zero and to signal a reset has occurred. (Consult with an expert to determine an appropriate address to use.) The rest of the parameters are analog channel#s whose readings provide the raw data to be summed. A zero channel# is ignored, but it occupies a “slot” in the output data structure.

The data structure of the accumulated data is as follows:

```
sum: ARRAY[1..4] OF Integer; { 4-word sum of beam data }
cnt: ARRAY[1..2] OF Integer; { 2-word sum of beam cycles }
tot: ARRAY[1..2] OF Integer; { 2-word sum of all cycles }
```

(Here, an “Integer” is a 16-bit word.) For each channel specified, a “slot” of 8 words is used starting at OUTADDR. The SSDN of the Acnet database entry for the reading property can include this OUTADDR. For example, if the source node were node 061E, and the base address of the data structure were 0x00002F00, one could then have the following SSDN structure: 1D02/061E/0000/2F00.

Upon reading this data, a host program can compute the accumulation (as a double precision floating point value) of each signal as follows, where $k=32768$:

```
acc:= ((sum[1]*k + sum[2])*k + sum[3])*k + sum[4];
nBP:= cnt[1]*k + cnt[2];
all:= tot[1]*k + tot[2];
```

These values need to be referenced to the set of values obtained during the last query by the host program, in order to get the amount of beam that has been accumulated over the last query interval. Upon conversion to engineering units, the data can be archived as needed. Note that this scheme works for multiple users without conflict.

The front end keeps 15 bits of precision in each word in order to maintain positive values that simplify the above formulas in hi-level language. (It also avoids the word swap problems that can result from differences with Vax data formats, since words are automatically byte-swapped by Fermilab networking hardware.) Note that a 60-bit long summation will never overflow in anyone's lifetime. Also, 30 bits of pulses at 15 Hz is more than 2 years. Site-wide power outages occur more often than that. A reset of the front end clears the accumulation area.

The host program will zero its own version of the accumulations according to its particular implementation. If the host program finds that the accumulation has dropped to a lower value than it had during its previous query, it can assume that the system has reset and restarted its accumulations. The most beam accumulation that could have been lost would be that which occurred since the last query. Assuming a one-minute query interval, for example, this should not be significant. (Typical times between resets of Linac front end stations are measured in months)