On the LBNF Spectrometer Duty Factor: How much beam time do we need ?

Paul Lebrun, Rowan Zaki

ND/Fermilab

Credits:

This work would have gone nowhere without the dedicated help from Mandy Rominsky, Eugene Schmidt, Anatoly Ronzhin, Dave Christian, and PREP support.

Thank you!.

Outline : What's the problem? How to solve it?

If we require to have only one PoT per “unit time”, and, if we want very large samples (many millions of pions, hundred thousand of kaons, muons), then we better make sure we can take the data before we have to give back the borrowed horns to LBNF, or the Fixed Target area back to other users.... or before the end of a MI FT run.

Thus a 1st order calculation of DAQ rate, run time duration is appropriate... And this depends on the LBNF spectrometer “architectural” issues..

Namely....

What's a “unit time” ?

Like any HEP detector the spectrometer is capable of detecting particles that are “well separated” in time, reconstructing tracks that come from a given interaction of a given PoT. One could compromise and record overlapping events, and let the offline pattern recognition & reconstruction code do its job... Is this consistent with our goal to measure flux of charged mesons to ~ 1% accuracy? Is this a good idea?

This depends on the detector technology, and front-end of DAQ capabilities. We also need an exquisite pattern recognition capability,

If drift chamber, with long drifts (~tens of cm) , & no timing ambiguities ==> few kHz max.

kHz is plenty enough to get many millions of events during weeks of running..!.

Except that we get ~ 4 to 6 (DUNE power supplies will be able to run at 1./0.6 Hz) Horn pulses, lasting only 50 microseconds, every minute... Dictated by (i) capability of the SY and external beam lines rep rate, one long spill/minute, and, (ii) the rep rate of the Horn power supply ~< 1 Hz. (M.I. / LBNF basic cycle time).

Not likely to be negotiable...

==> 6 * 50 μsec/60 ~ **duty factor <~ 5 10^{-6}**

DAQ rates in the spectrometer, 1st

a. Detector Aperture: Horn C downstream Outer Conductor radius is about 0.634 m. Thus, to get the spatial distribution of the flux, we need to cover ~ 1.26 m^2. Assuming the entrance aperture of the small aperture LBNF spectrometer (LBNFS) is 9 by 3 inches, at any relevant position, LBNFS will then cover only 1.07 % of the area where the flux needs to be measured. If we use a large aperture spectrometer (LBNFL), 100 time faster!.

b. Pion rate out of the Horn, per incident proton on target (PoT): We assume 0.1 for round number, We can quibble by a factor of a few here. (We need more G4LBNF/Spectrometer simulation, work in progress..)

c. Required Statistical precision: Let us take 1% relative yield measurement, so statistically, we need at least 10,000 pions. => 10,000 PoT per Horn setting, and spectrometer position (LBNFS case) . Or, ten millions PoT to cover the entire 1.26 m^2 area.

These numbers are for LBNFS, 100 times less PoT (or horn pulses) is needed if LBNFL is selected.

DAQ rates in the spectrometer, 2nd

d. Duty factor to get one and only PoT per unit time (if this is a requirement): Assuming the primary proton intensity per 53 MHz rf bucket can be dial to the required value, with an average probability of 50% (the so-called MI slow spill duty factor). Poisson statistics (1 and only 1), gives us an factor of 0.36 => duty factor further decrease by a factor of ~3...

We are not sure about this!... *Is the instantaneous (within one 53 MHz r.f. bucket) delivered M.I. beam current constant across the 4 second spill duration?*

This is also a concern for a slower detector... What if the ~50 μsec horn pulse comes when the M.I./S.W delivers just a set of super-bucket?

DAQ rates in the spectrometer, bottom line

We now compute a run duration, where a run covers the entire area/solid angle at the downstream end of hornC. We need ~10^7 PoT, and we can take ~10^4 r.f. bucket every minutes (4 * 50 μsec/20 ns). At most, some 3,000 of them will have one and only one proton (at best) So, we need ~ 44 hours of beam, per measurement, or LBNF Spectrometer setting.

We think these rates are acceptable, we will be able to take multiple such runs, modifying the alignment of the horns, target position, etc, per months..

But this assumes a DAQ 100% efficient, and, a

perfectly smooth low intensity beam.. And .. 100% targeting efficiency...

All based on the assumption that we need 1 and only 1 PoT per r.f. bucket!.

Previously discussed, perhaps, but let me review again the reasoning:

The beam spot size, ex-situ, “nano-intensity”, will be quite different from the beam spot size in the real target, real chase, running at nominal intensity. So, the plan is measure the flux as a function of proton position on target.. Since the nano-beam at the fixed target area will be less focused (slow extraction!) than the real beam, many protons will graze the ~5 mm wide target, instead of hitting it at the center.

The probability to find a neutrino progenitor downstream of the horn strongly depends on this position. We typically produce with G4LBNF neutrino spectra that are integrated over the surface area of the beam spot size. With the LBNF spectrometer, we plan to determine the position of each proton on target, with a silicon strip or pixel detector upstream of the target.

We are not planning to have intermediate tracking between the target and HornA..Simply, there is no room for it.. So, the pions/kaons detected in LBNF spectrometer can not be unambiguously assigned to a given PoT hitting the target at a given X,Y, on target, unless we have one and only one PoT on target.

One and only 1 PoT per r.f. bucket!... Is it needed?

If we have the knowledge of the focusing & transmission efficiency, target to decay pipe, for a given pion/kaon at given momenta, then, we could afford to have more one PoT per “unit time”, or r.f. bucket..

This is precisely one of the parametric functions we would like to measure.

Yes, we could perhaps simulate, re-weight the output of the simulation, and iterate to match the data.. A complicated procedure, subject to bias... The final output will be model-dependent, because of the inherent ambiguities in unfolding this neutrino flux.

So, I really, would prefer to carry out this program with one and only one PoT at a time.

To put it bluntly, simplicity in the analysis is asset we want to have..

Duty Factor measurement at FTBF.

- So, going back slide 6, if we ask for 1 PoT per r.f. bucket, how many times do we have one and only one PoT ?
- No clear answer at FTBF. Note that it is beam line dependent, and intensity dependent, and may change from day to day depending on the M.I. QXR tuning They run at typically at (at most, for now ?) ~ 4 millions of particle per spill. Or much lower..
- It would be nice to know, if we ask for that intensity, or a factor 10 higher, as we have some 200 million r.f. buckets per spill, how many time we have one and only proton in each bucket? (~1/3 if Poisson distributed).
- Conceptually:
  - Take a charged particle a minimum ionizing particle (MIP), detect it, fast, <~ 20 ns, and keep detecting with no dead time, for ~ 4 second.
  - Record a sequence “0, 1 or >2” MIP data, or, conversely, the r.f. bunch count (at 53 MHz) or the r.f. bucket with a signal, or >1 MIP..
  - Take data, analyze.

Status...

- Got two, dual readout small (2x2 cm^2, 1x1 cm^2) . With old and trusty (crusty?) PMTs (designed ½ century ago).
- Got a NIM crate with linear amplifier, discriminator, NIM logics, NIM → TTL
  - Noisy Lecroy modules, same old, (PREP equipment)
- DSR4 board used to gain balance, pulse shape studies. Digitize at 5 GHz max, used typically at 1 GHz, allowing us to take some 1.4 μsec long (~70 r.f. buckets) wave forms, every ~ 10 msec or so (data rate limited, got ~350 trigger per sec. Max). Not continuous across the spill.
- Got Sr90 data, as well as muons from FTBF back wall.
- Installed in the beam, at location 1.b, upstream of CMS HL tracking test, on May 4.
- Taking parasitic data (May 5, May 10, May 11,...)

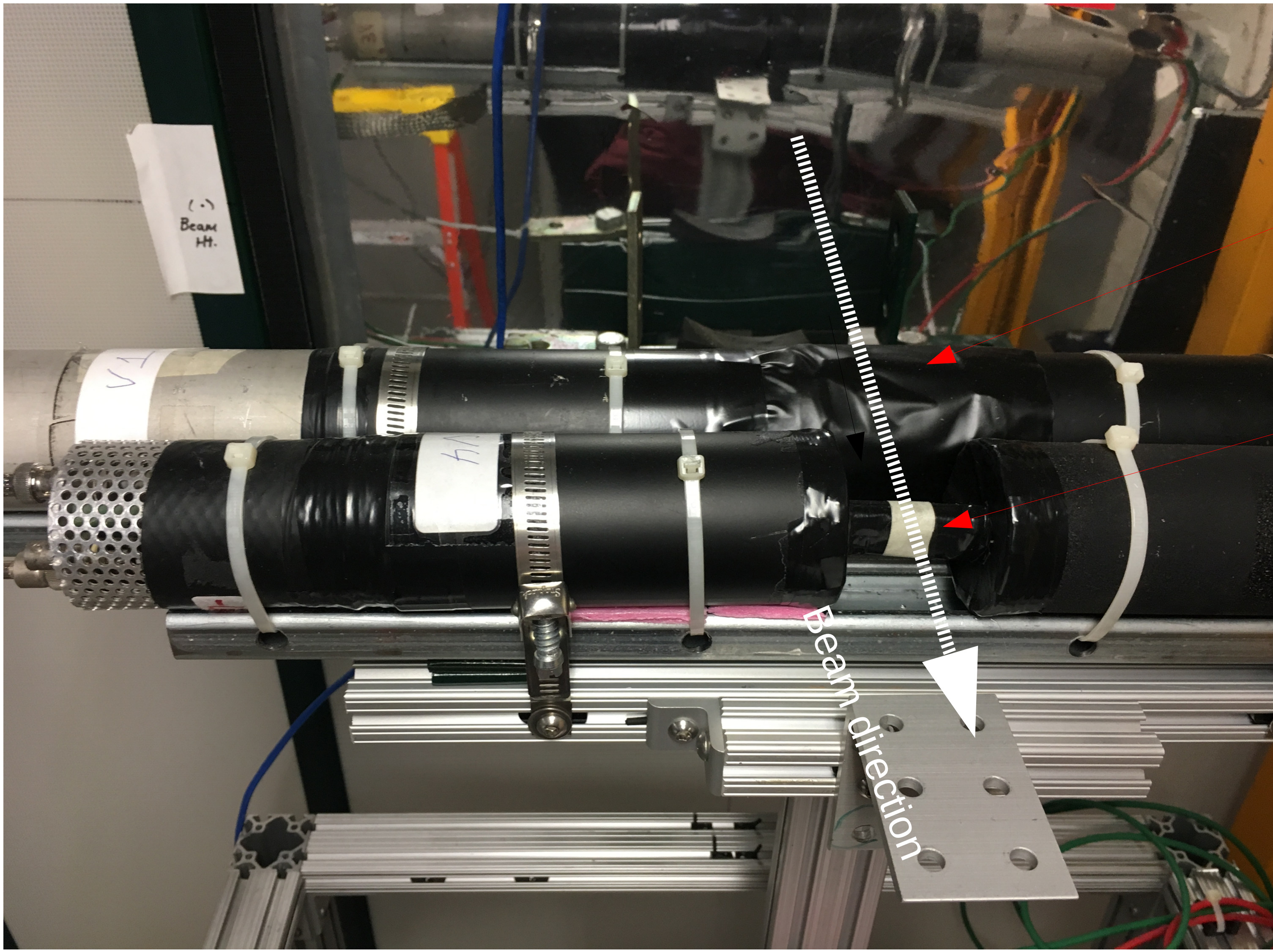
Counters..

Old & new ..

DRS4 board..

Dual readout counters

Old & new ..

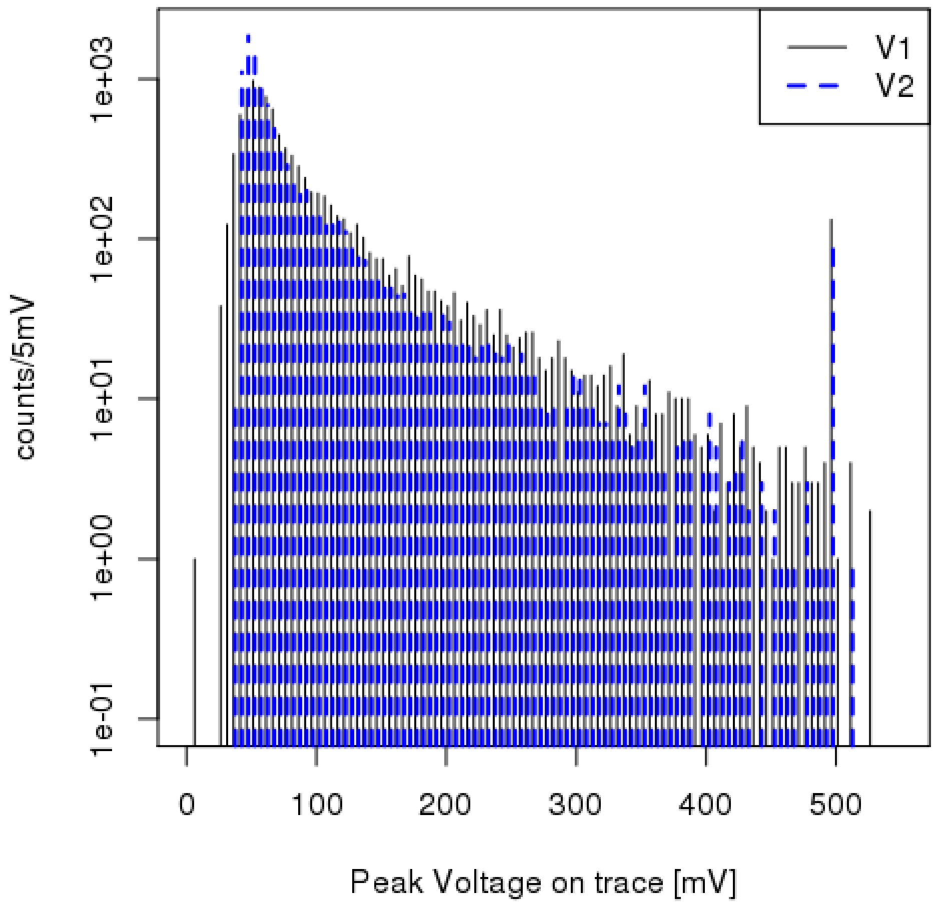


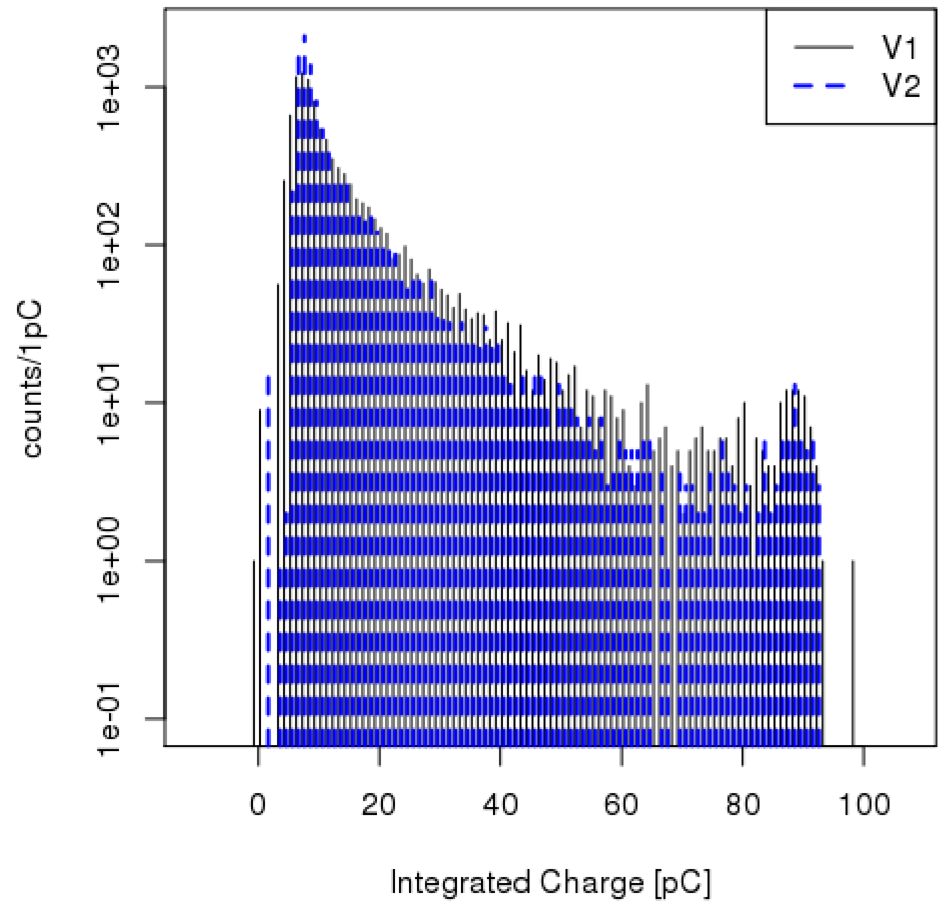
$2x2\ cm^2$ scintillator

$1x1\ cm^2$ scintillator

Current Status..

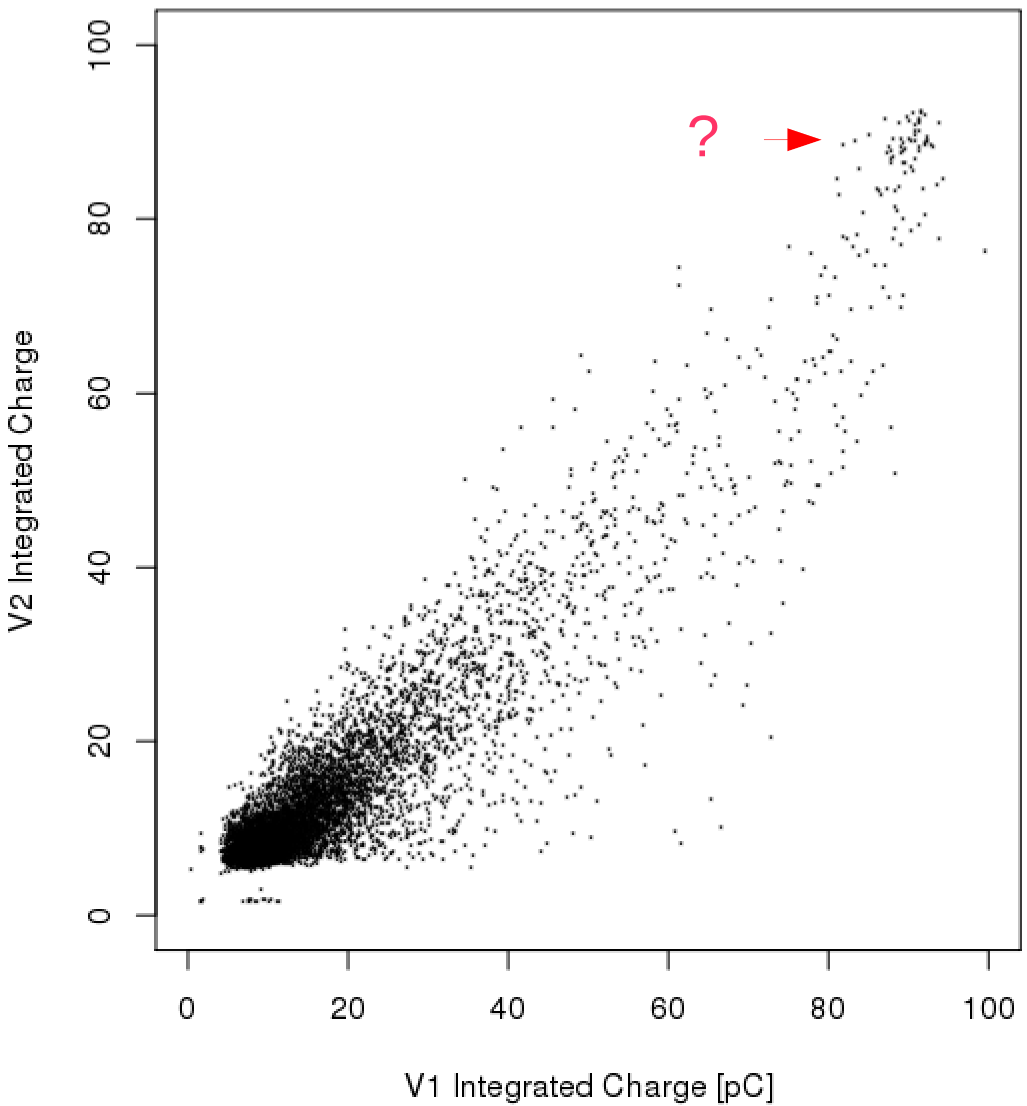
- Taking data with the DRS4 oscilloscope..
  - Max DAQ rate ~ few hundred 4-channel wave forms per M.I. spills.
- Got a simple XML based decoding & analysis package in https://cdcvs.fnal.gov/redmine/projects/lbnfspectrom-dutyfactor-st1
  - No root based (I haven't given up on using the R statistical package, so the output are event by event simple ASCII files)
  - Can be expanded.
- V1 & V2 PMT voltage set such that the mean MIP is about 75 mV. Linear fanned-out to create a trigger for the DRS4





Distribution of peak voltages from DRS4 module, and integrated charge (assuming 50 Ω termination) , obtained from 10,000 DRS4 triggers, May 11 2017. Parasitically! The Mtest intensity was ~3 e9, the PWC & trigger counters of Mtest recorded about 30,000 particles per spill. The DRS4 board was digitizing at 1 GHz, for about 1 μsec, and we can take ~250 such waveforms per spill.

Landau tails



The tails of the distribution of signal strength nicely correlate.

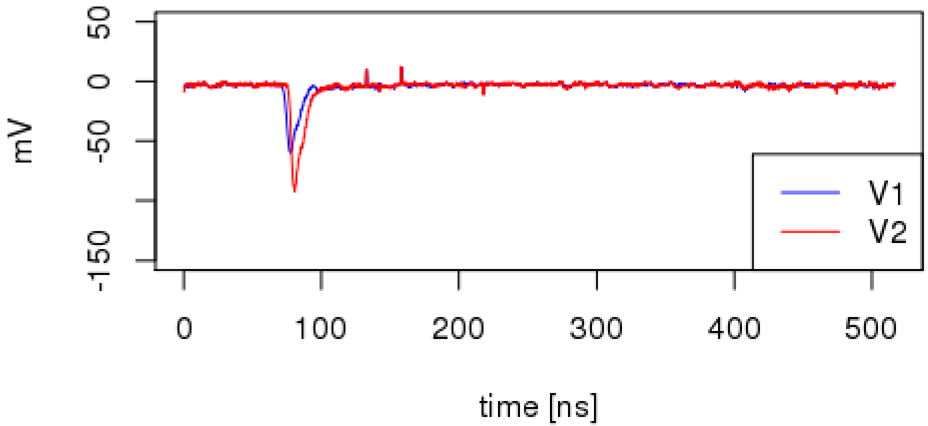
Landau tails in the energy loss..

Note the overflow, around 80 pc (500 mV, max allowed, over a few 1 ns.)

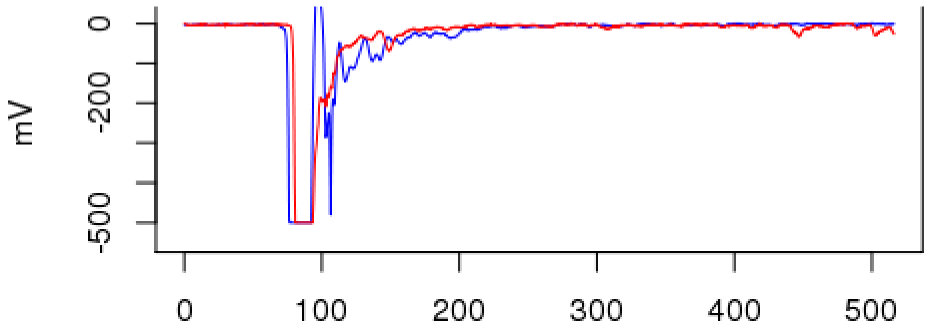
Multiple particle per r.f. bucket, due to multiple primary protons per r.f. buckets, or more likely given the intensity at which we were running, hadronic interactions produced upstream of the counters...

The signals from the 1x1 cm^2 counter were triggered by (V1, V2) logic coincidence. Unfortunately, no such nice correlation and no nice Landau like energy deposition. Voltage have been increased, but no good response. ==> work with the 2x2 cm^2 for now..

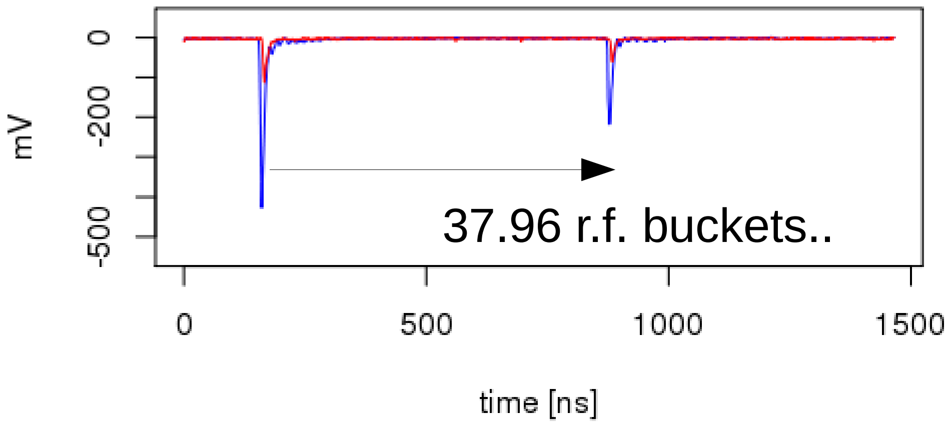
Looking for multiple ~3 ns pulses per trace



Single particle, “MIP”.



Multiple particle, super-bucket or upstream interaction? Taken on May 11, at ~ 100,000 counts/spill on F:MT6SC1 (or ~ F:MT6SC2)



Clean bucket separation..
Taken on May 05, at ~ 40,000 counts/spill on F:MT6SC1

Counting the occupied buckets..

Only for ~1 μsec, ~ 250 times per spill (DRS4 DAQ limitation)

We have 1.8 10^8 r.f. buckets/spill. With 10^5 PoT/spill, should have a r.f. bucket occupancy of 5.6 10^{-4}. Over ~ 10,000 traces, with ~50 r.f. “witness buckets”, I should have collected dozens of multiple MIP signals already..

Got only 2 clean such events, so far, for 20,000 traces. Why?

Simpler experiment

As suggested by Dave Christian, we also have simple scalers, coincidence V1+V2, and V1 High threshold.. (0.25 $\rightarrow$ 0.75 Lecroy disc...)

Pros: easy! Just count the high pule heights, normalize to MIP counts, and you'll get the fraction of unusable beam..

But, not easy to calibrate the discrimination threshold.. unless we have a DRS4..

What's next?

More information available from DSR4 data.. (And we can take more data from our office..)

Repeat previous DRS4 runs, at different intensities. (from lowest possible, say few thousands ppp on MT6SC1, to highest (few millions, higher if possible.)

We are scheduled to be able to set the intensity of the beam on Memorial day week-end
Such measurement should take only ~ one shift.

Acquire, borrow, but not steal, a NIM+/CAPTAN boards, to get continuous information on bucket occupancy, logic signal (low/high discriminator threshold) over a significant part of the spill. Perhaps, scheduled before the end of the F.Y. 2017 run..

Conclusion

We need to think about the LBNF Spectrometer duty factor. This is a high precision measurement, and, in addition to high statistics, we need to repeat the measurement many times, varying the LBNF beam parameters (Horn alignment, primary beam focusing..)

A “pre-prototype” of a FTBF “ r.f. occupancy profiler” is being assembled. And tested.

Side benefit: Other FTBF users might be interested, and existing Cerenkov signal and scintillating counters could be used for this purpose, once we have NIM+/CAPTAN DAQ board, and demonstrate the method works..