A NEW TOOL FOR LONGITUDINAL TOMOGRAPHY IN FERMILAB'S MAIN INJECTOR AND RECYCLER RINGS

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Abstract

Tomographic reconstruction of longitudinal phase space was developed for use in particle accelerators by Hancock [1] at CERN in the 1990's and is being implemented for operational use at Fermi National Accelerator Laboratory(FNAL) for the first time. The existing resistive wall current monitors [2] in FNAL's Main Injector and Recycler rings provide ideal input for tomographic reconstructions. The software package called Tomography And Related Diagnostics In Synchrotrons (TARDIS) aims to be an easy to use diagnostic tool for producing tomographic reconstructions and analysis of longitudinal phase space. Operational use at FNAL will include the continuous reconstruction of full Booster batches at key points during the the Main Injector and Recycler timelines with minimal user input providing near real-time updates of machine performance as well as trends over many cycles. The design and performance of this system is presented.

DEVELOPMENT GOALS

The main goal of this project is to use the existing resistive wall current monitor hardware and electronics to create longitudinal reconstructions of measured profiles for diagnostic purposes at certain points during the cycle, namely, injection, slip-stacking recapture, and flat-top, as applicable, through an easily configureable interface. Advanced operation should include the ability to record data along with all relevant parameters for offline reconstruction and analysis of non-standard beam experiments.

Secondarily, the code base for the reconstruction operations should be encapsulated for ease of extension to more complicated dynamics, batch processing, and custom studies. A standard form for turn-to-turn maps has been developed as part of this effort to encourage development.

SYSTEM OVERVIEW

The program which runs in the Main Control Room at FNAL, TARDIS, is designed to be run continuously triggering off of a specified clock event, e.g. transfer of a Booster batch to the Main Injector. For standard operating scenarios there should be almost no user setup required since everything about the batch structure, machine, and cycle is known beforehand. A single green button in the main window, seen at upper right in fig. 2 is enough to get the program continuously reconstructing batches at injection (or indicate that the oscilloscope is being used by another program). Users are able to customize the scope setup, the machine, reconstruction, and preprocessing parameters, but suitable defaults are given or determined algorithmically otherwise.

Written in C++ and relying on FNAL's ACNET Console Libraries for communication with the accelerator complex and much of the ROOT [4] framework for the GUI, plotting, and analysis functions, we aimed to develop an easily extensible object oriented program. Much effort has been put into encapsulation in order to make the code useful outside of the control room environment. Specifically, any code unique to operation at FNAL can be easily excluded and the program built for standalone use.

A simple block diagram of the signal reconstruction from electronics to user interface is shown in fig. 1

The rightmost portion of the figure, enclosed in blue, comprises our contribution. There are five distinct elements, each made up of several classes, coordinated with controller classes. In standalone programs the controller classes can be omitted and their functionality reimplemented as needed. Each element of the software is outlined below.

Data Acquisition

First is Data Acquisition. This module handles the low-level communication with the accelerator complex. From here the scope is armed on the appropriate clock event, and the parameters of a specially designed 'mountain range trigger box', which communicates directly with the RF clock, are set. The code contained here is specific to FNAL and would need to be reimplemented if the code was used elsewhere as an online tool. This processes is eased via a simple controller class which needs only implement several functions that provide communication with the program's main controller.

Preprocessing

The general aim of the preprocessing module is to take the raw signal data, with some global parameters such as RF frequency, and generate a set of individual bunch profiles to be reconstructed by the tomography algorithm. The pp must check the requested data exists, i.e. batch number 1,2 or 3 etc., and then decide where the signal is relative to the RF buckets. The pp module has a similar structure to others in the program. A controller object is created that can create other objects to perform the various tasks, called Finders, because they typically leave the data unchanged returning what they've found, e.g. baseline, batch or bunch start and end points etc.

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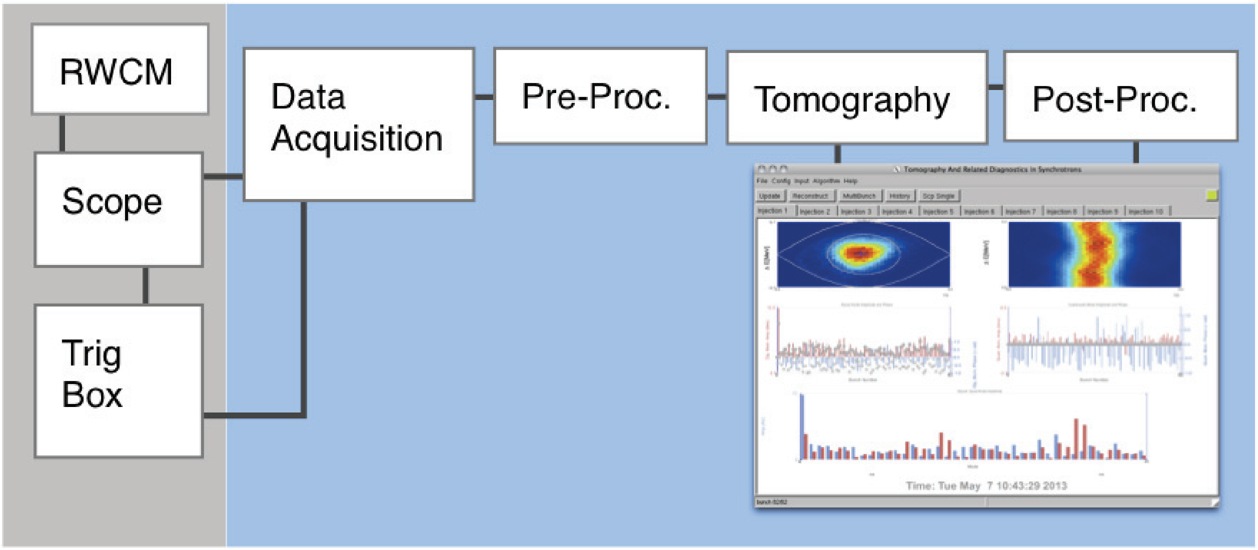

Figure 1: Chart showing path of data. Enclosed segment to right indicates the work discussed in this document.

Finding the bucket middles in the RWCM signal is perhaps the most important task to be accomplished. The current method makes two main assumptions: The bucket centers are evenly spaced, determined by the RF frequency with negligible beam loading, and any bunch oscillations average out over a long enough period of time.

The sum of multiple frames covering at least a synchrotron period (preferably more) is taken. This sum of frames is then partitioned into sets a bucket spacing wide and the central moments calculated for occupied sets. The partitioning is then shifted by a bin and the central moments recalculated, this is repeated. The partitioning that gives the mean of all the central moments closest to half the bucket length is used.

After the bucket middle positions are defined bunch profiles are easily generated.

Preprocessing is a more general operation than data acquisition. At the very least the bunch finding operation should provided some level of preprocessing even if a novel batch structure is present. If desired, it is relatively simple to add new functionality to the preprocessor.

Tomographic Reconstruction

Preprocessed data is then passed to the tomography portion of the code. A set of maps discretizing the motion of particles through the phase space is needed. All of the beam physics is contained in these maps. We have determined that under normal operating conditions the inclusion of space charge in our mapping dynamics provides only a minimal improvement in reconstruction quality and a significant cost in reconstruction time. The main advantage to eliminating space charge, with respect to speed, is that one set of maps can be made ahead of time for a set of machine and reconstruction parameters and used to construct arbitrarily many bunches.

A standard form for the maps has been developed that makes certain tradeoffs between storage space and speed, opting for more complex operations at the map building stage and simpler operations at reconstruction time. The form developed is general, and arbitrarily complex machine models can be used to track test particles and build maps. As long as the standard form is followed more detailed tracking can always be added. A detailed account of the standard form developed is beyond the scope of this paper, but will be available in code documentation.

Following Gordon [3] several variations on the ART algorithm are available: ART, ART with a damping term, and ART2. The integral of the reconstruction in each case is normalized to the bunch 'charge' measured in uncalibrated scope counts calculated from the preprocessed profiles, effectively rendering all realizations 'fully constrained'. Maintaining the scope count normalization allows relative comparison of feature intensity in different bunches across a batch, as in fig. 3.

Post-processing

The standard output from a reconstruction includes: the reconstructed images, the input data used in the reconstruction, the projection of that image into profiles at each frame, (a 'perfect' reconstruction would show the last two to be the same), and discrepancy at each iteration for each bunch. Discrepancy is a measure of the closeness of the final image projections and the input profiles adopted from Gordon [3] and is used to ensure the algorithm is converging. (Non-convergence is one indication that the dynamics of the system are not consistent with the model used.)

Any analysis done on the output of the reconstruction process falls under the heading of post-processing. Currently we use the images to estimate the emittance of bunches, a straightforward measurement to make once the

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images have been obtained. We also measure the dipole moment of the charge distribution in each image (and higher orders in the future), as well as the coupled bunch power spectrum of the moments across the batch following Sacherer [5]

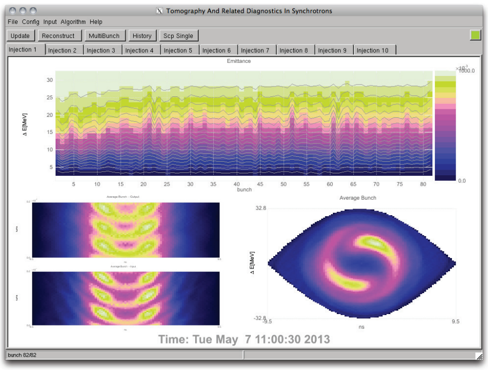

Figure 2: One possible layout for the main window showing an emittance plot (top), average bunch reconstruction (lower right), projection of reconstruction (middle left), and average input data (lower left). Another can be seen in fig. 1

Interface

The Main Control Room interface is simple and highly configurable. A main window will display any combination of up to 10 plots in any configuration. Typically, this window is used for plots displaying information relevant to an entire batch: emittance plots, average bunch reconstruction, coupled bunch spectra, etc. Fig. 2 shows the main window in one possible configuration with input data, output projections, reconstructions, and emittance calculations shown. Another view can be seen in as part of fig. 1. As stated in the introduction to this overview, a single green button in the upper right initiates the reconstruction loop.

A separate window is used for examining the reconstructions of many bunches at once (up to a full Booster batch) since this tends to be a large plot. Fig. 3 shows this frame displaying only the reconstructions of a Booster batch at injection to the Main Injector.

Another dedicated window allows the setting of all non-data acquisition parameters, i.e. machine, preprocessing, reconstruction.

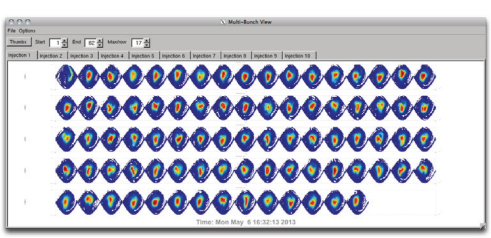

Figure 3: Full batch window showing reconstructions of Booster batch upon injection into the Main Injector.

A dedicated window (not shown) is used for data acquisition: obtaining a scope lock, setting the trigger and scope parameters, and previewing the acquisition window. This window is related to the data acquisition code, so encapsulation of these functions allows the program to run in offline mode and process previously collected data or examine the output from earlier reconstructions away from the Main Control Room.

A timestamp and information about the current settings are displayed at the bottom of every window that displays plots by default.

Planned, but not yet implemented, is a window to allow plots of measurements taken over time to be displayed to indicate long term trends in machine performance.

NOTES ON PERFORMANCE

This software utilizes OpenMP to implement parallelization. Because maps are typically precomputed when running in online mode the only parallelized portion of the code is the reconstruction of multiple bunches. The loop over distinct bunches in a batch is split using a parallel 'for', leaving the reconstruction of each bunch intact with regards to parallelization. After studying some data taken before the previous long shutdown it has been decided to reconstruct the signal at 5.0GHz sample rate. Under typical running conditions, with precomputed maps and parallelization on one of the five core CPU's in the FNAL Main Control Room a full 81 bunch injection can be reconstructed and analyzed in approximately 15-20 sec. This timing can vary greatly depending on the value of a number of parameters including, number of frames, convergence limit, number of particles per cell, etc.

FUTURE DEVELOPMENT

FNAL's Main Injector and Recycler are scheduled to come online in 2013 after a long shutdown. TARDIS will be tested during recommissioning with a solid foundation of features necessary to act as a simple diagnostic tool. Planned upgrades include the ability to specify more complicated RF waveforms, a mode for computing space charge corrections, and release as a standalone analysis tool.

REFERENCES

[1] S. Hancock, P. Knaus, M. Lindroos, European Particle Accelerator Conference, Stockholm, Sweden, 22 - 26 Jun 1998. Publ. in: Proceedings, (CERN-PS-98-030-RF).

[2] B. Fellenz and J. Crisp, "An Improved Resistive Wall Monitor" in proceedings of Beam Instrumentation Workshop (BIW98), p. 446, 4 7 May 1998, Stanford, California, USA.

[3] R. Gordon, A tutorial on ART, IEEE Trans. Nucl. Sci., NS-21, pp78-93, 1974.

[4] Rene Brun and Fons Rademakers, ROOT - An Object Oriented Data Analysis Framework, Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, Nucl. Inst. & Meth. in Phys. Res. A 389 (1997) 81-86. See also http://root.cern.ch/.

[5] F. J. Sacherer, "Methods of Computing Bunched Beam Instabilities," CERN/SIBR/72-5, p.26, September 1972