Michael Borland
borland@aps.anl.gov

SDDS: A Modular Toolkit for Accelerator Simulation, Control, and Operation

Michael Borland

Operations Analysis Group

Advanced Photon Source

Argonne National Laboratory

Michael Borland
borland@aps.anl.gov

Outline of Presentation

- History, Concept, and Implementation
- Self-describing data
- Self-Describing Data Sets (SDDS) protocol
- SDDS-compliant program toolkits
- Examples from commissioning
- Examples from operations

Michael Borland
borland@aps.anl.gov

A Brief History of SDDS

- Originally (1993), we sought to provide general-purpose software for the APS commissioning team:
  - collect and analyze data
  - perform experiments
  - develop control algorithms
- We planned to have high-level applications (HLAs) written based on *algorithms* developed during commissioning.
- The commissioning concept worked so well that it was used to make HLAs directly.
- The same concept works very well for accelerator simulation.
- SDDS used at IPNS, BESSY II, RHIC, and SLAC.

Michael Borland
borland@aps.anl.gov

Concept

- Make a system where programs are operators that sequentially transform data files.
- If programs read/write the same type of file, they can be used in any order.
- Make programs completely generic and not application-specific.
- Well-suited to on-the-fly work because no programming is involved.

Michael Borland
borland@aps.anl.gov

Examples of the Concept

- Simple lifetime measurement:
  acquire | takeLog | polyFit | display
- Robust lifetime measurement:
  acquire | takeLog | polyFit | removeOutliers | polyFit | display
- Beam history analysis:
  acquire | FFT | smooth | peakfind | display
- Find the noisiest power supply:
  acquire | computeStats | collect | sort | display
- Chromaticity measurement data reduction:
  acquire | smooth | peakfind | collapse | polyFit | removeOutliers | polyFit | display

Michael Borland
borland@aps.anl.gov

Implementation

- Used a *simple*, *common* self-describing data protocol for datasets.
- Wrote generic, commandline programs for
  - data collection
  - data analysis
  - graphics
  - process control
- Used pre-existing script languages (e.g., Tcl/Tk) to
  - coordinate programs.
  - record complex sequences for reuse.

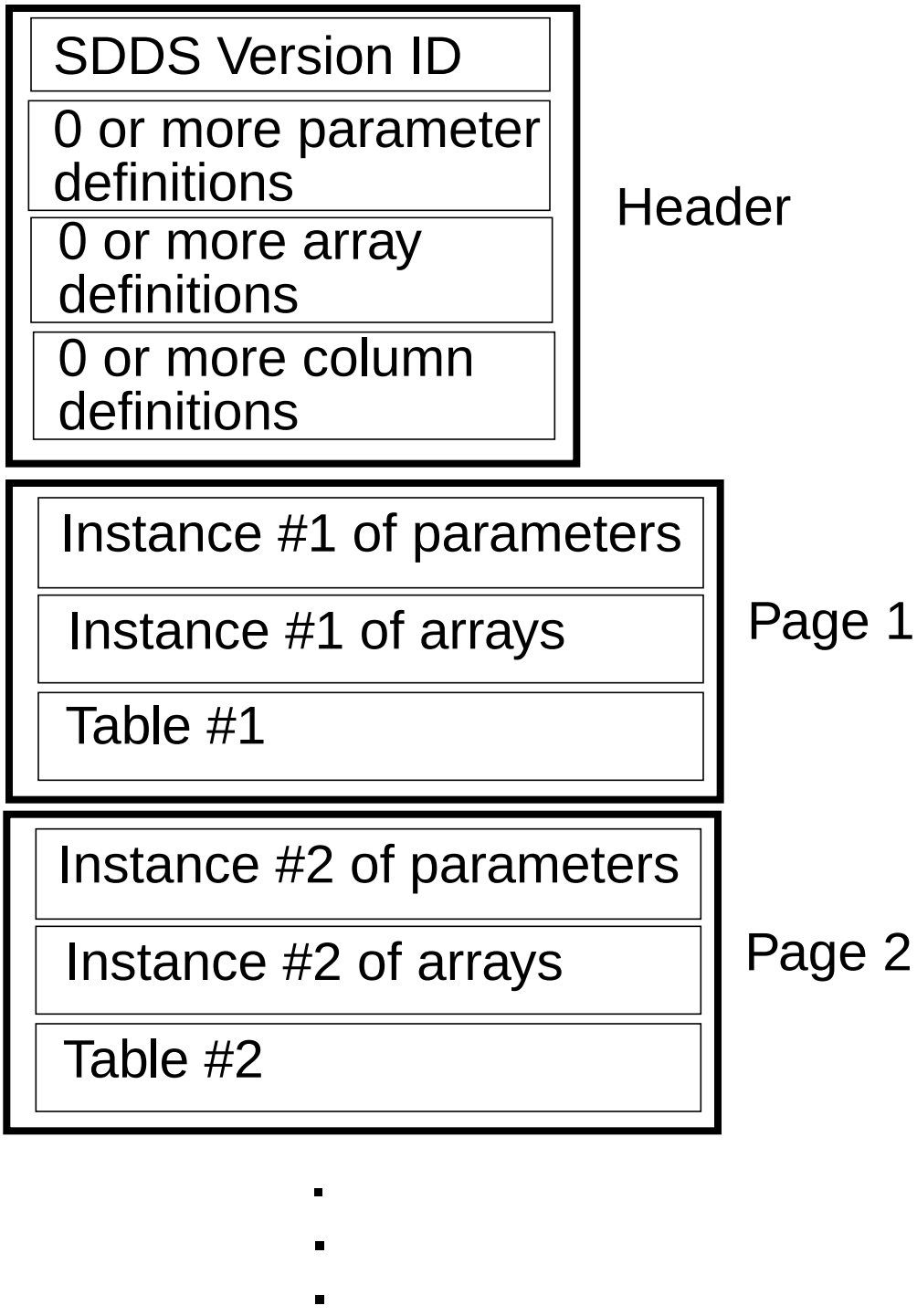
Michael Borland
borland@aps.anl.gov

What is Self-Describing Data?

- Self-describing (SD) data is identified and accessed by name only.
- SD data files include meta-data about data, e.g., units and data type.
- Advantages:
  - genuinely generic programs possible
  - data elements may be added to files without “breaking” existing programs
  - data tends to be self-documenting
  - source of data (measurement, simulation) is irrelevant

Michael Borland
borland@aps.anl.gov

SDDS Data Model



Michael Borland
borland@aps.anl.gov

Examples of Control System Data Stored in SDDS Files

- Accelerator backup/restore files.
- Oscilloscope setup data.
- Archival data from continuous machine monitoring.
- Beam dump records.
- Alarm history.
- Magnet conditioning instructions.
- Feedback matrices for energy and trajectory control.
- Response matrices for orbit correction.
- Orbit correction configuration files.
- Waveform data from oscilloscopes and network analyzers.
- Ramp tables for booster power supplies.

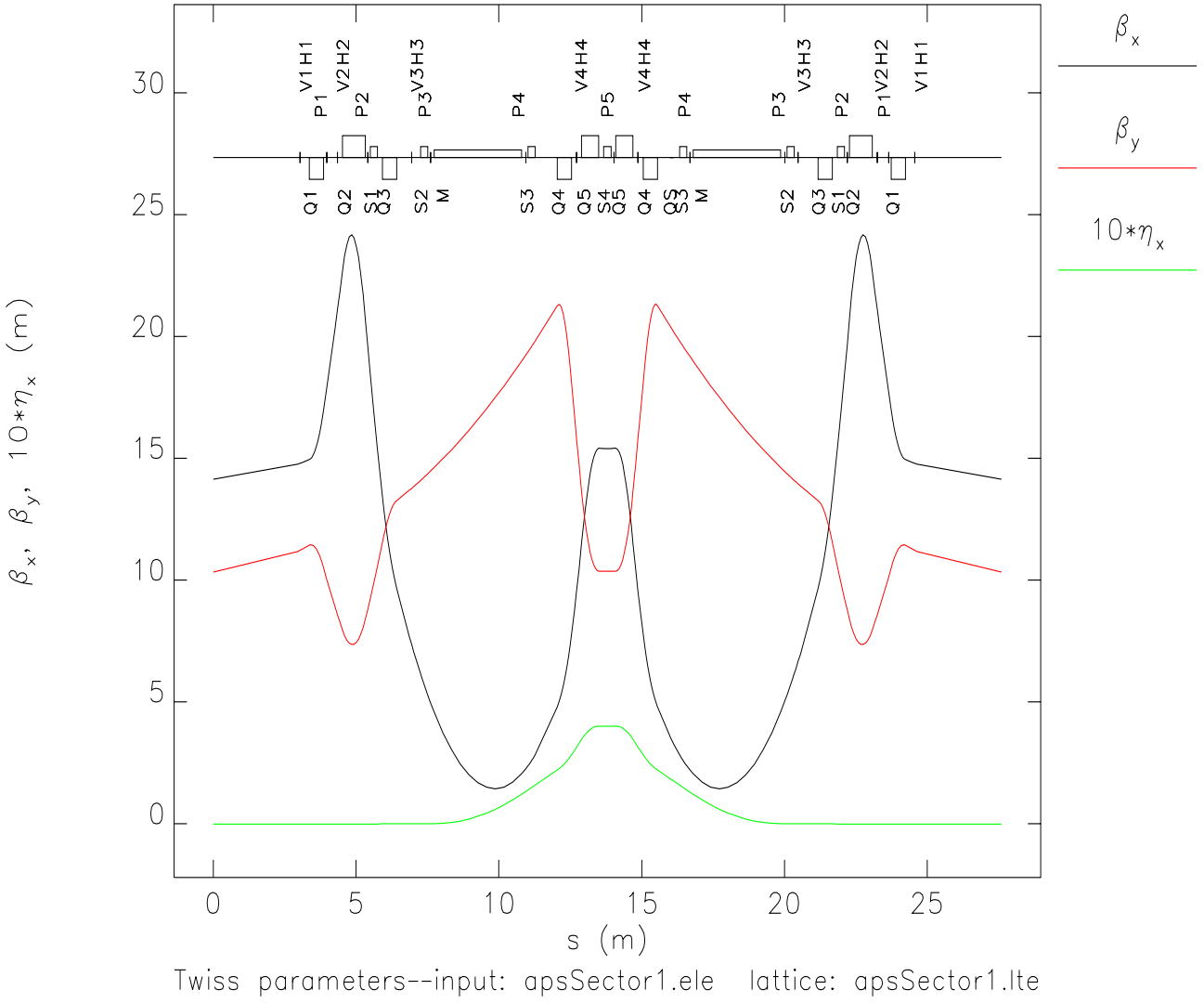
Michael Borland
borland@aps.anl.gov

Examples of Simulation Data Stored in SDDS Files

- **elegant**—general accelerator modeling
  - lattice functions, matrices, orbits, floor coordinates, etc.
  - orbit correction matrices
  - phase-space coordinate input/output
  - element perturbation input/output
- **spiffe**—electromagnetic PIC simulation
  - EM field maps
  - EM fields at cavity probe points
  - particle snapshots in time and space
  - cavity boundary output
- **shower**—EGS4 interface
  - input particle coordinates
  - shower product phase-space output
  - material properties input
  - radiation dose in distributed materials

Michael Borland
borland@aps.anl.gov

APS Twiss Parameters Plotted with 'sddsplot'



Michael Borland
borland@aps.anl.gov

SDDS Toolkit Programs

- SDDS is used by a group of about 70 generic data processing and display programs.
- Most of these “SDDS Toolkit” programs both read and write SDDS files
  - They can be used in sequence.
  - Even simple tools become highly useful when supported by the toolkit.
- About 20 EPICS-specific programs use SDDS.
- Development is decentralized—anyone can add a tool.
- There is no single, large program to maintain.
- All programs are commandline driven and hence scriptable.

Michael Borland
borland@aps.anl.gov

SDDS Toolkit Capabilities

- Device-independent graphics.
- Equation evaluation.
- Data winnowing.
- Statistics and histograms.
- Polynomial, exponential, and gaussian fitting.
- Correlation and outlier analysis.
- Matrix operations (e.g., SVD).
- Cross-referencing, sorting, and collation.
- FFTs and digital filtering.
- Protocol conversion to/from SDDS.
- Text printouts of data.

Michael Borland
borland@aps.anl.gov

SDDS-Compliant EPICS Programs

- Time-series data collection.
- Time-series statistical data collection.
- Glitch-based data collection.
- Synchronized data collection.
- Alarm data collection.
- Experiment execution.
- Process variable save/restore/ramp.
- Workstation-based feedback.
- Workstation-based feedforward.
- Workstation-based optimization.
- Oscilloscope state save/restore.
- Magnet conditioning setup.

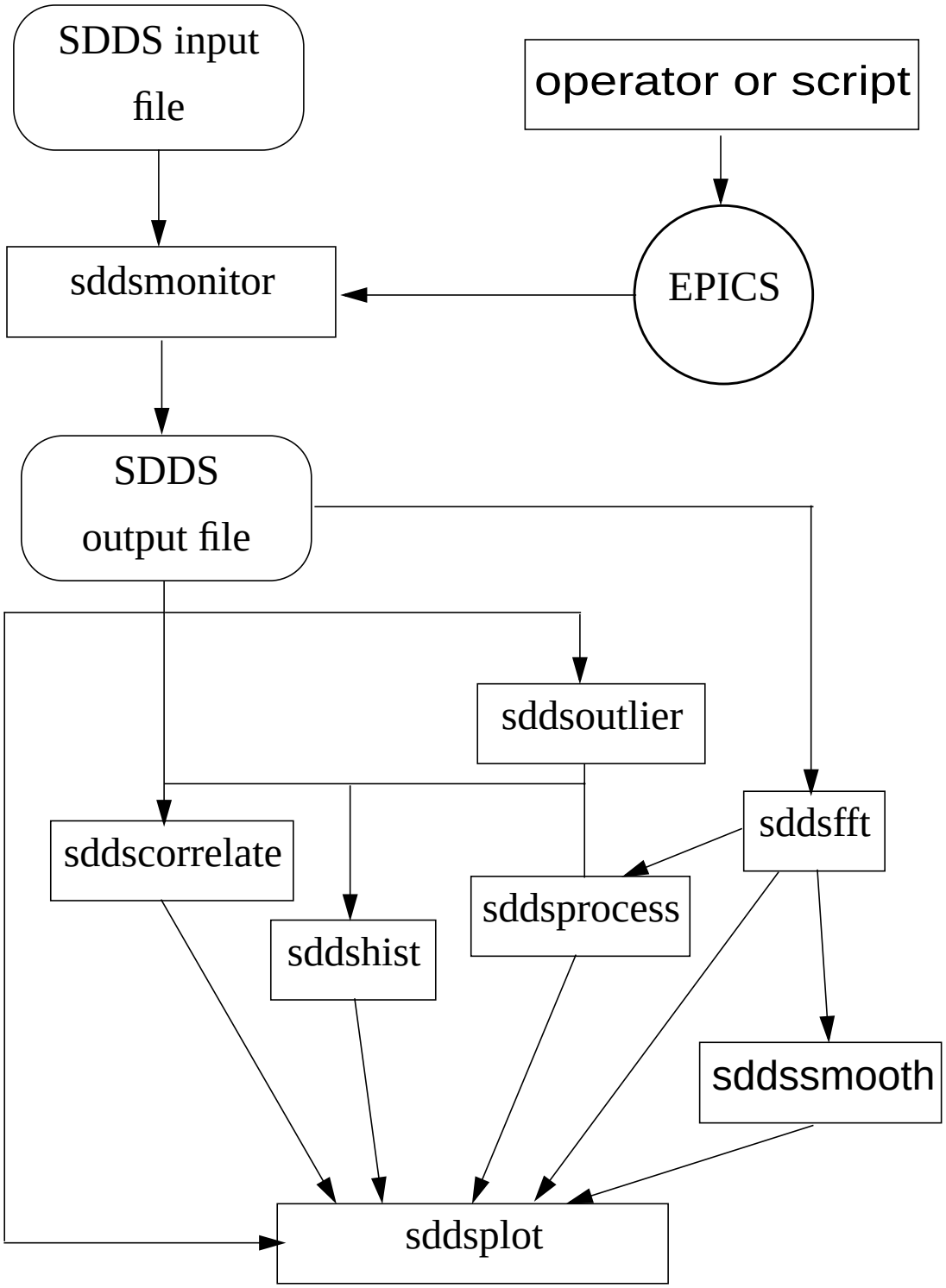
Michael Borland
borland@aps.anl.gov

SDDS Monitoring Programs

- Four variants:
  - Logging scalar PV values.
  - Logging statistics of same.
  - Logging scalars grouped as vectors.
  - Logging waveform and scalar PVs.
- Common features
  - SDDS-configured.
  - Acquisition at specified time intervals or on command.
  - Conditional data logging.
  - Erase, append, or generation mode for files.
- Glitch/trigger mode for scalar logging uses a circular buffer for pre- and post-trigger samples.

Michael Borland
borland@aps.anl.gov

sddsmonitor Application Example



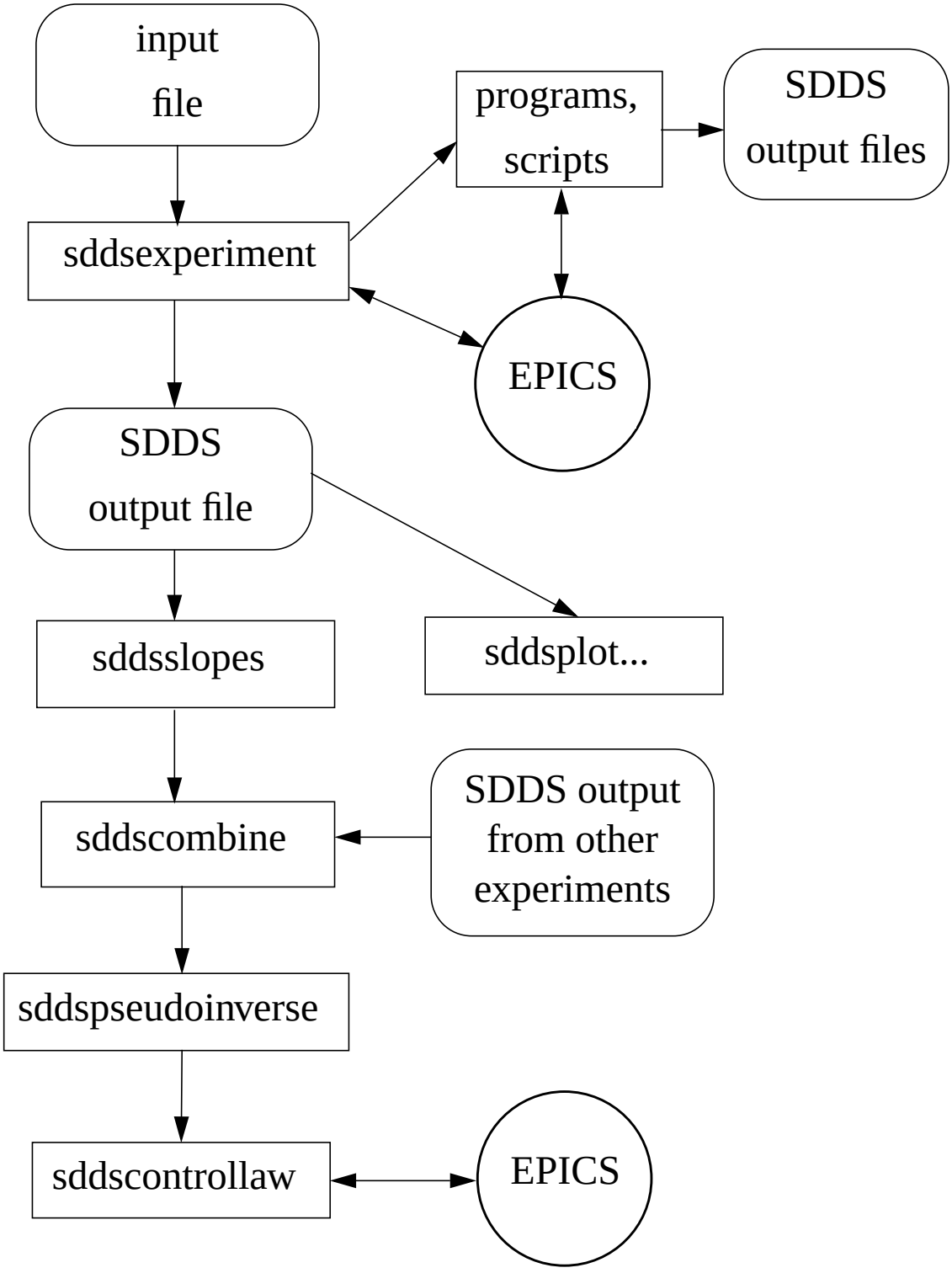
Michael Borland
borland@aps.anl.gov

SDDS Experiment Programs

- **sddsexperiment** performs N-dimensional scans and scalar data collection.
- Any number of actuators may be linked to each scan index. Actuator settling time and response testing supported.
- Actuator setpoints may be specified in several ways:
  - Min, max, number of data points.
  - Values from an SDDS file.
  - An equation with one of these supplying input values.
- Actuator variation may be relative or absolute, with optional reset.
- Optionally does averaging, computes error bars, and rejects bad data points.
- External scripts may be linked to scan indices.

Michael Borland
borland@aps.anl.gov

sddsexperiment Application Example



Michael Borland
borland@aps.anl.gov

sddscontrollaw Overview

- Generic workstation-based feedback program.
- Usually used for integral control:

$$A_{i+1} = A_i - GME_i$$

  where A is the vector of actuator values, E is the vector of readbacks, M is the correction matrix, and G is the gain.
- Takes SDDS files for
  - feedback matrix, with actuator and error readback names
  - process variables to test and valid ranges
- Will hold PVs to existing values, to given values (from SDDS file), or to zero.
- Safety features (optional):
  - actuator change limits
  - readback change limits
  - inhibit operation based on PV values
  - “run-control” semaphore system for suspend/resume/abort
  - activity logs

Michael Borland
borland@aps.anl.gov

Applications of sddscontrollaw

- Maintains constant energy and trajectory from linac using an experimentally-derived matrix.
- Corrects orbit in PAR.
- Steers/maintains SR orbit using theoretical matrix and orbit despiking filter.
- Maintains SR injection trajectory.
- Adjusts power levels from SR klystrons as beam current changes.
- Regulates power levels from linac klystrons.
- Used by a script that allows on-the-fly creation of one-readback, one-actuator control loops.

Michael Borland
borland@aps.anl.gov

Some Commissioning Activities Performed Using SDDS and Scripts

- orbit/trajectory response matrices
- orbit correction algorithm development* (SR)
- dispersion and chromaticity* (SR, PAR)
- automated first-turn steering* (SR)
- beta-functions* (SR)
- dynamic aperture* (SR)
- tune shift with amplitude (SR)
- phase-space tracking (SR)
- tune shift with current (SR)
- BPM intensity dependence* (SR)
- integer tune (SR, booster)
- energy aperture for stored beam* (SR)
- physical aperture search* (SR)
- insertion device effect on orbit and tune* (SR)
- x-ray BPM “pollution” tests (SR)
- septum leakage field using beam (SR, PAR)

Michael Borland
borland@aps.anl.gov

- lifetime vs scraper position, bump height* (SR)
- beta-function and dispersion correction* (SR)
- linear coupling reduction (SR)
- kicker bump matching (SR)
- BPM-to-quad offset measurements* (SR)
- search for sources of beam motion (SR)
- power supply ramp correction* (booster)
- automated injection steering (booster)
- longitudinal injection acceptance (PAR)
- bunch length and damping time (PAR)
- rf voltage calibration using beam (PAR)
- kicker waveform shape using beam (PAR)
- automated beam-excited HOM search (PAR)
- energy gain vs input power, frequency, and temperature (linac)
- klystron gain measurements (linac)
- search for cause of energy oscillations (linac)
- emittance measurements and beta-function matching* (linac)

Michael Borland
borland@aps.anl.gov

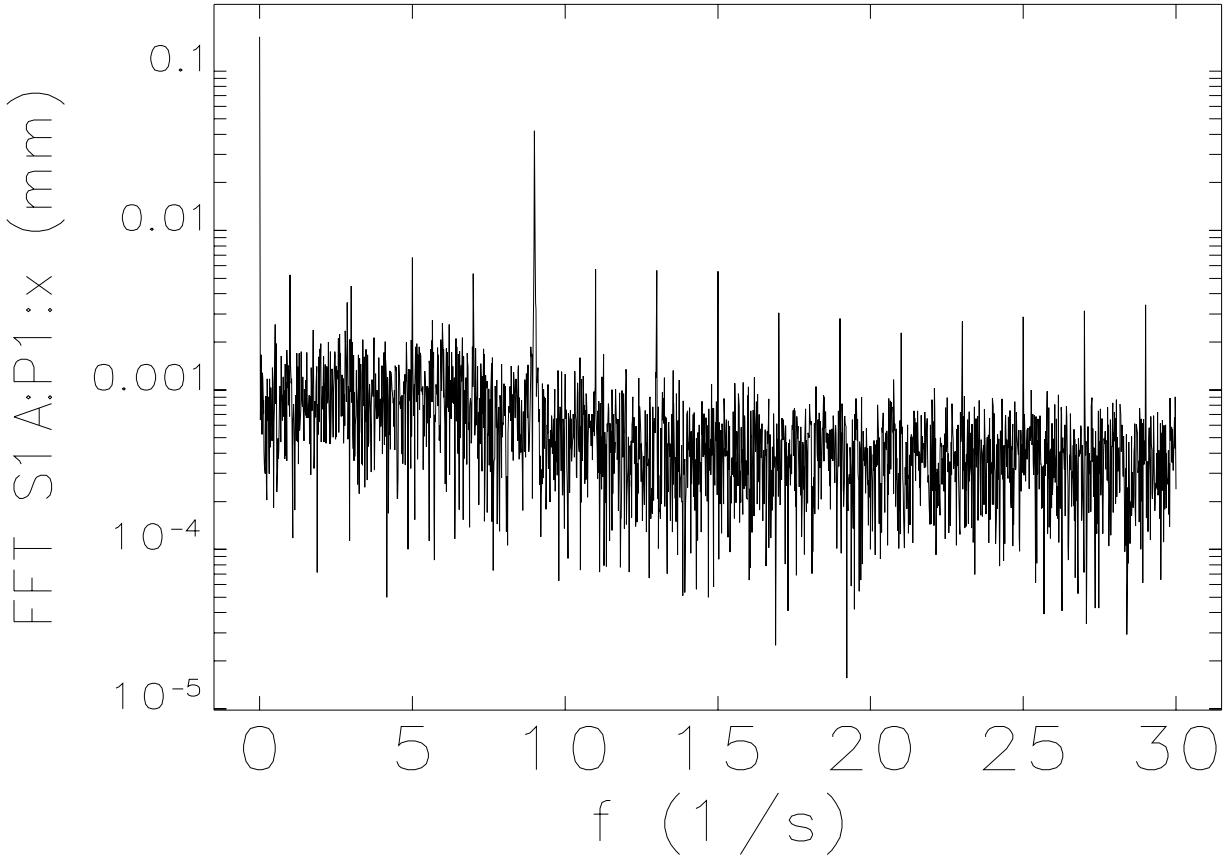
SR Beam History

- The storage ring BPM system has several history buffers that store samples for selected BPMs at rates from 60Hz to 271kHz.
- Data is available in EPICS waveform records, which we download with **sddswmonitor**.
- For example:

```
sddswmonitor slowAP1.wmon \
      slowAP1.sdds -step=1

sddsprocess slowAP1.sdds -pipe=out \
  -define=column,t,"Index 60 /",units=s \
  | sddsfft -pipe=in slowAP1.fft \
  -columns=t,*A:P1*

sddsplot -column=f,FFT*A:P1* slowAP1.fft \
   -separate -mode=y=log,y=specialscales
```

Michael Borland
borland@aps.anl.gov

Sa[illegible] [illegible]story



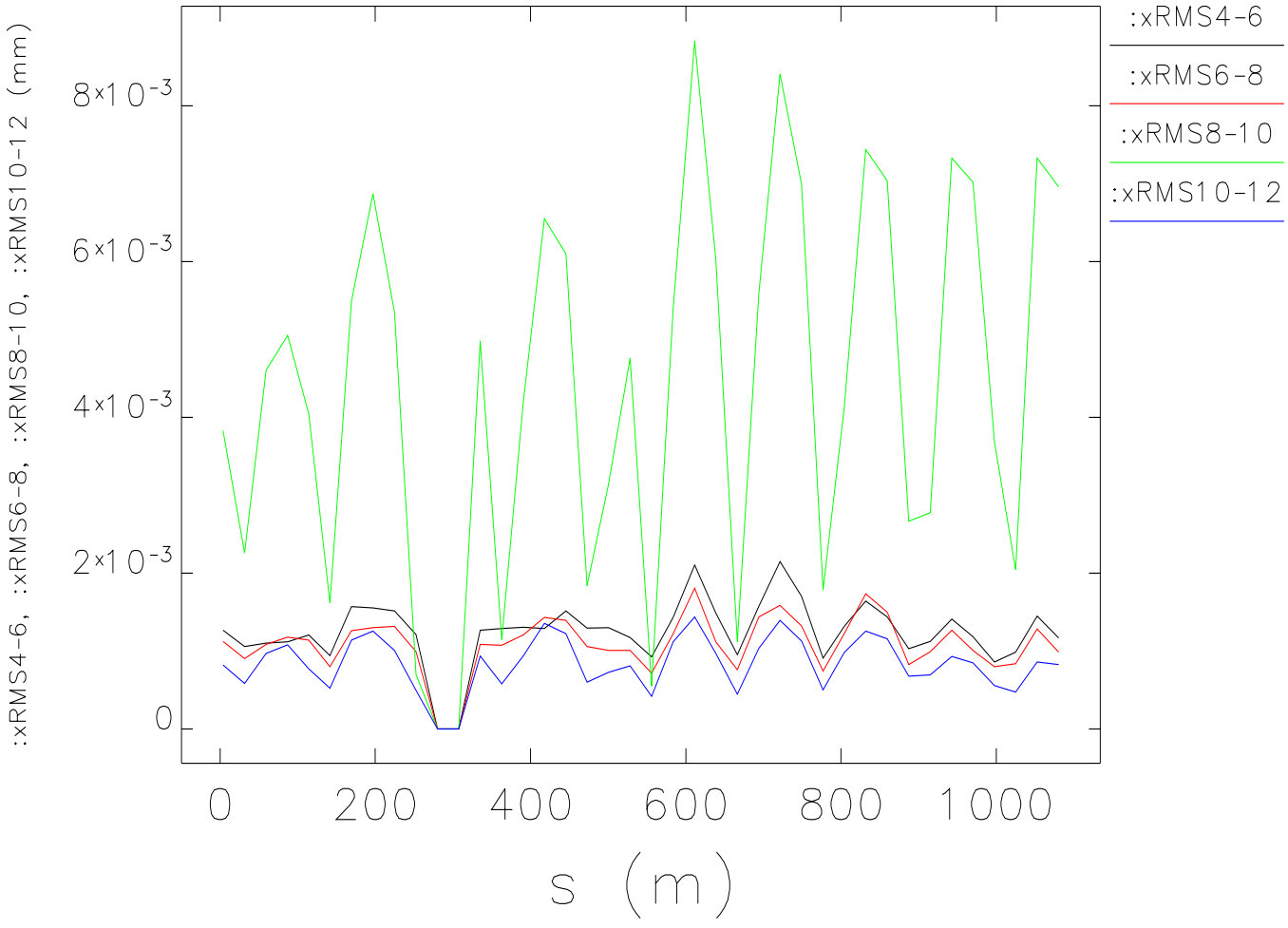
Michael Borland
borland@aps.anl.gov

Script for Analysis of Power in Bands

```
#!/bin/sh
# \
exec oagtclsh “$0” “$@”

# find RMS amplitude in 2-Hz-wide bands as a function
# of position in the ring

exec sddsprocess slowAP1.fft -pipe=out \
   -process=FFT*,rms,%sRMS4-6,func=f,lower=4,upper=6 \
   -process=FFT*,rms,%sRMS6-8,func=f,lower=6,upper=8 \
   -proc=FFT*,rms,%sRMS8-10,func=f,lower=8,upper=10 \
   -proc=FFT*,rms,%sRMS10-12,func=f,lower=10,upper=12 \
    | sddscollapse -pipe \
    | sddscollect -pipe \
    -collect=suffix=:xRMS4-6 -collect=suffix=:yRMS4-6 \
    -collect=suffix=:xRMS6-8 -collect=suffix=:yRMS6-8 \
    -collect=suffix=:xRMS8-10 -collect=suffix=:yRMS8-10 \
    -collect=suffix=:xRMS10-12 -collect=suffix=:yRMS10-12 \
    | sddsprocess -pipe \
    -edit=column,BPMName,Rootname,%/FFT//  \
    | sddsxref -pipe aps.twi -match=BPMName=ElementName \
    -take=s -reuse=rows \
    | sddssort -pipe=in -column=s slowAP1.bands

exec sdds
        -colu
```

Michael Borland
borland@aps.anl.gov

Plot of Band Analysis of Beam History



Michael Borland
borland@aps.anl.gov

SR Dispersion and Chromaticity

- This experiment involves variation of the rf frequency while measuring tune and orbit.
- **sddsexperiment** is used to drive the experiment and collect orbit data. Two script calls are used by **sddsexperiment** to start the network analyzer sweep and collect tune spectra.
- After completing the experiment, the orbit data is processed using **sddsvslopes** to fit the position vs rf frequency for each BPM in each plane (720 fits). These are then converted to dispersion using the momentum compaction factor (**sddsprocess**).
- The chromaticity analysis script combines the spectra (**sddscombine**), finds the tunes (**sddsprocess**), computes the effective energy offset (**sddsprocess**), and does fits for the chromaticities (**sddspfit**).

Michael Borland
borland@aps.anl.gov

PAR Orbit Response

- **sddsexperiment** used to measured response of all BPMs to each corrector.
- To execute the experiment, one uses the command like

sddsexperiment P1H1.exp P1H1.sdds

- A simple script with a loop is used to create each experiment file from a template, then run it.
- To plot the results, use **sddsplot**, e.g.:

sddsplot -column=P1H1,P1P2.x P1H1.sdds

- Data analysis consists of running **sddsslopes** for each corrector pair to find the slope and its error for each BPM.
- The data from a group of scans can be combined for use with **sddscontrollaw** for orbit correction.

Michael Borland
borland@aps.anl.gov

Sample sddsexperiment Input File

```
! File P1H1.exp
! define what to measure (SDDS file)
&measurement_file
   filename=PBPMs.mon,
   number_to_average=5, include_sigma=1
&end
! define what to vary
&variable
   control_name=P1H1:CurrentAO
   column_name=P1H1, units=A,
   relative_to_original=1,
   index_number=0, index_limit=5,
   initial_value=-2.0, final_value=2.0
&end
! set global parameters and run
&execute
   post_change_pause=3
   intermeasurement_pause=0.5
&end
```

Michael Borland
borland@aps.anl.gov

PAR Damping Time

- A fast photodiode viewing synchrotron radiation was digitized with an HP54542A scope using sequential single-shot mode.
- Transferred to workstation via floppy.
- Converted to SDDS with **hpif2sdds**, one segment per page.
- 750 traces viewed with **sddsplot** using X-windows movie feature.
- Processed with **sddsprocess** to invert sign of signal, find baseline and spread, add segment times, etc.
- Analyses plotted with **sddsplot**.
- Each trace fit using **sddsgfit**.
- Fit results collated with **sddscollapse.**
- Processed with **sddsprocess** to put in resolution correction and remove bad points.
- Bunch length and centroid vs time displayed with **sddsplot**.

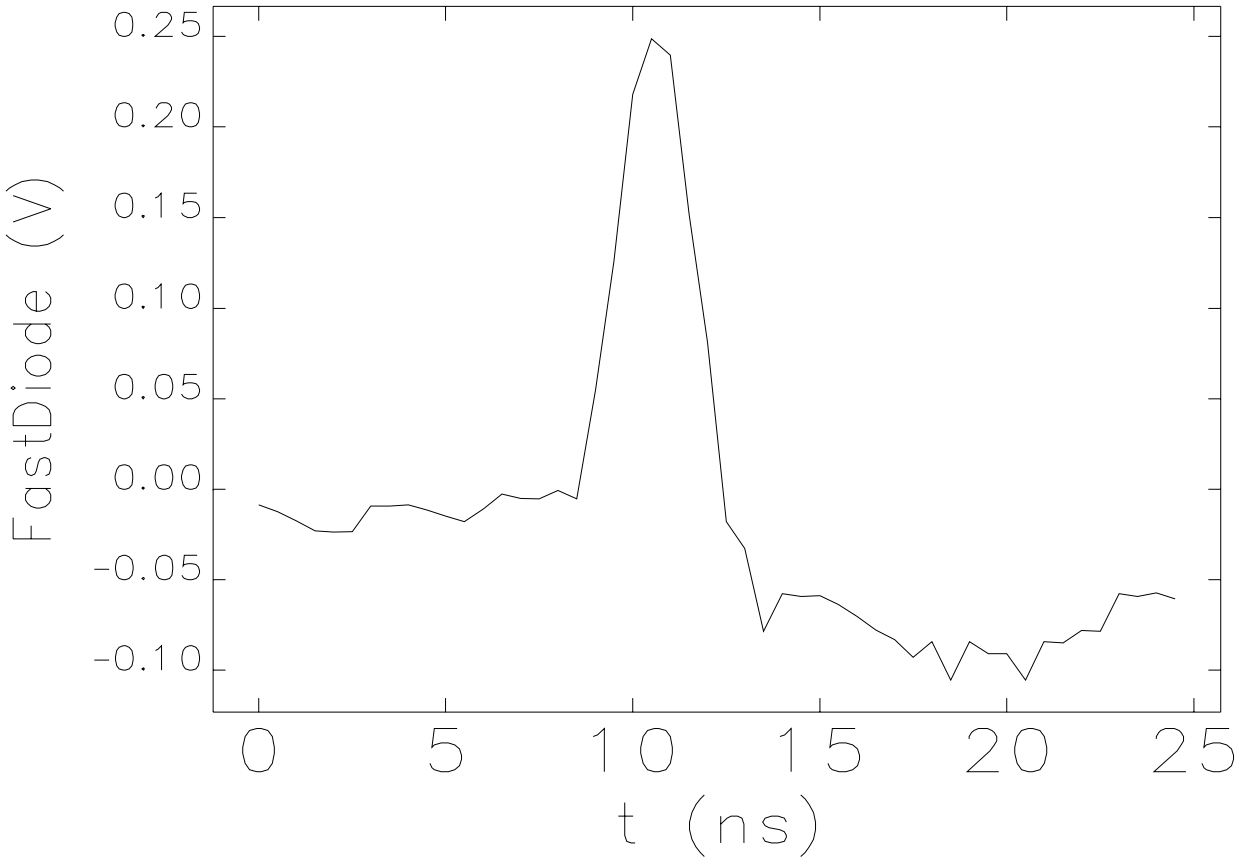
Michael Borland
borland@aps.anl.gov

- Part of bunch length data vs time fit with **sddsexpfit** to find longitudinal damping time.

- None of the tools used were developed with this application in mind.
- First analysis took about 15 minutes.

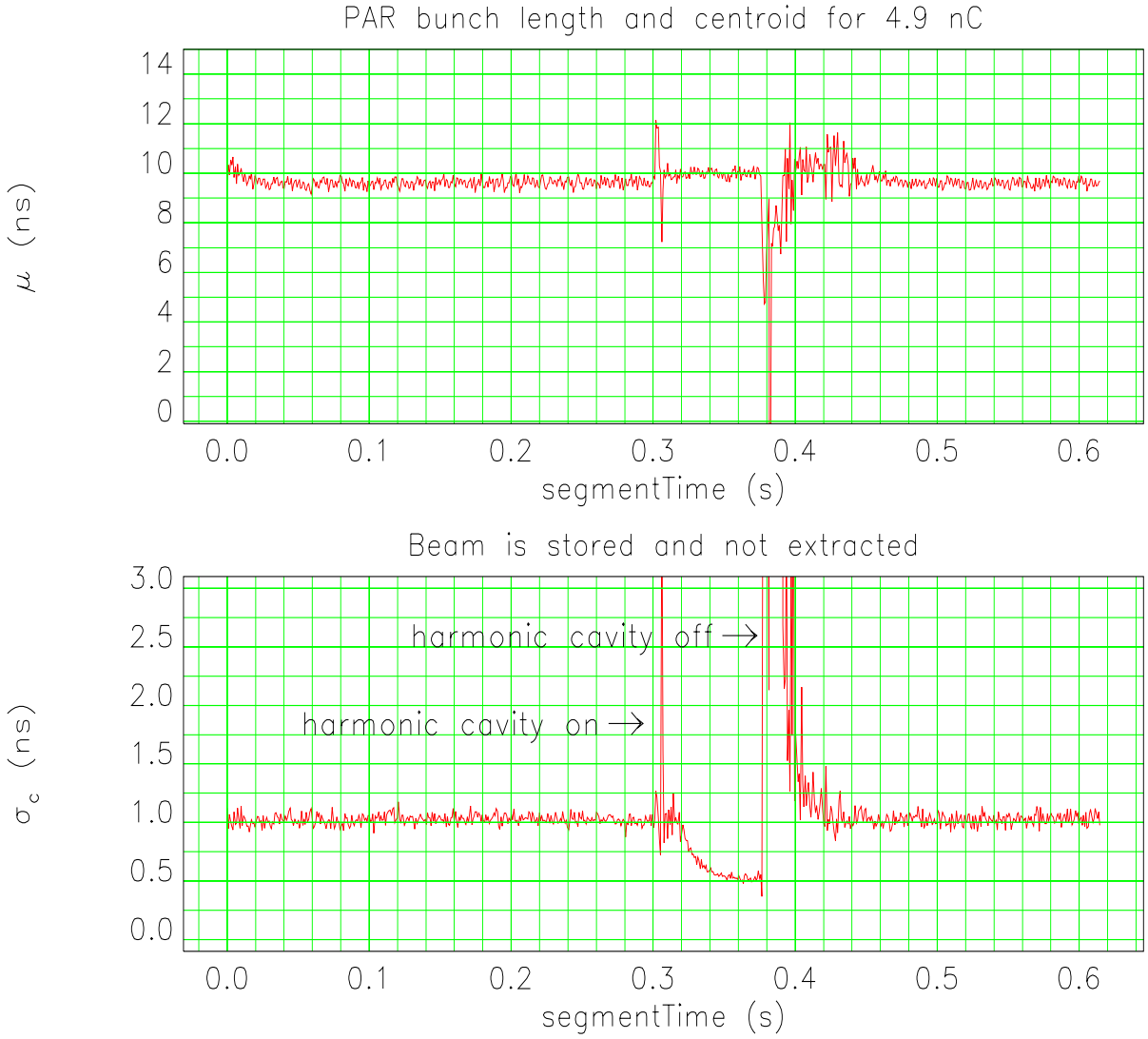
Michael Borland
borland@aps.anl.gov

Typical Photodiode Signal
—One of 750 Pulses—



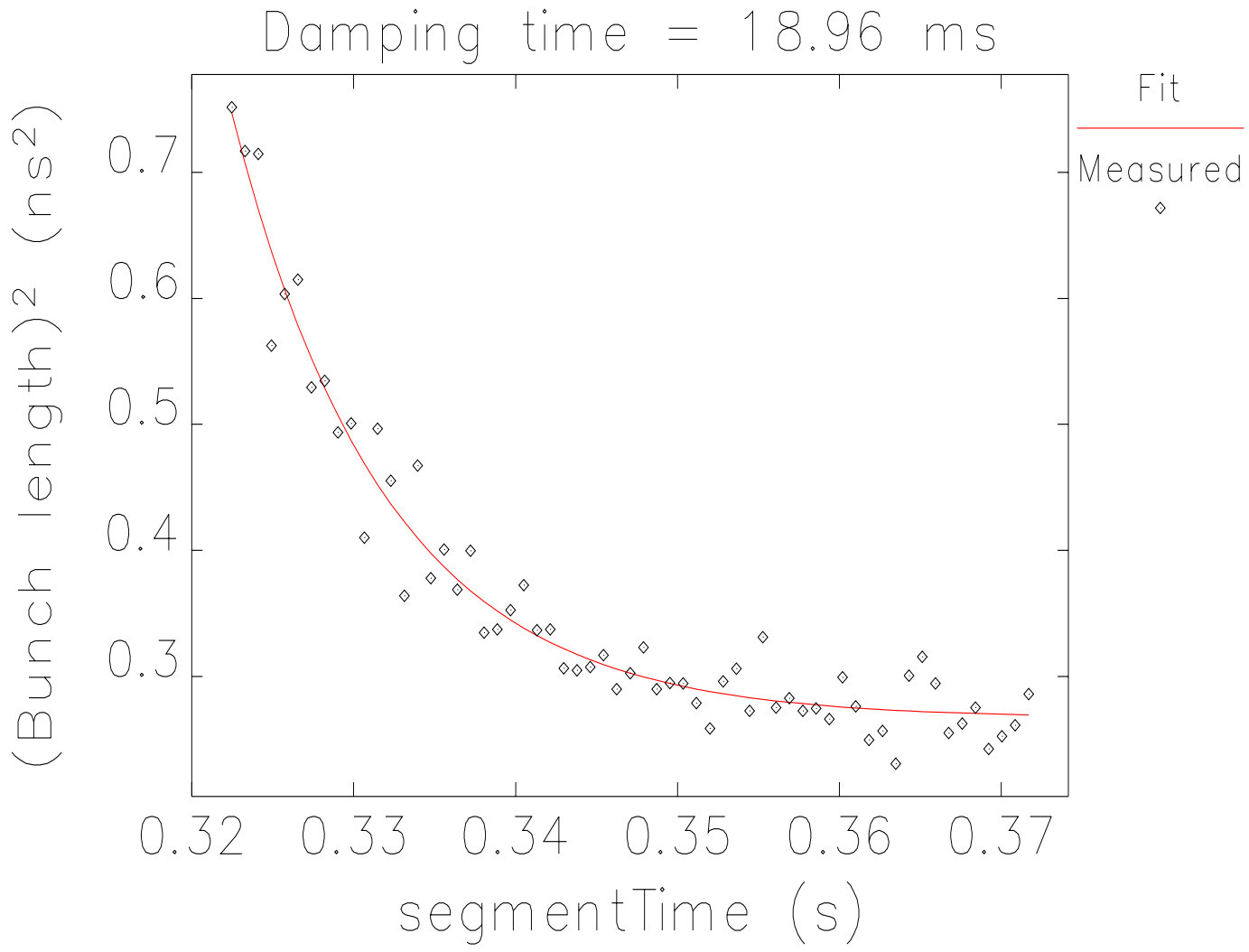
Michael Borland
borland@aps.anl.gov

Bunch Parameters vs Time



Michael Borland
borland@aps.anl.gov

Fit to Obtain Damping Time



Michael Borland
borland@aps.anl.gov

SDDS and Routine Operation

- The work invested in SDDS-based Tcl scripts transfers readily to operations.
- APS depends on SDDS-based Tcl/Tk scripts for routine operation.
- Presently ~26GB of SDDS data for APS operations
  - 48k PVs in configuration management
  - 22k PVs in time-series logging
  - 10k PVs in alarm logging
  - 2k PVs in glitch logging

Michael Borland
borland@aps.anl.gov

SDDS-Based Applications Used Routinely by Operations

- Save/Compare/Restore system for managing accelerator configurations.
- Data review and analysis tools for time-series, glitch, alarm, and beam dump data.
- Orbit correction configuration.
- BPM intensity dependence compensation.
- Workstation-based feedback, e.g., orbit correction, rf voltage control, linac energy/ trajectory control.
- Steering of ID and BM beamlines.
- Automated startup/setup of power supplies.
- Machine performance analysis and archiving, e.g., RMS beam motion, tunes, fill pattern.
- Workstation screen configuration.