A Universal Postprocessing Toolkit for Accelerator Simulation and Analysis

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Advanced Photon Source

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Common Problems with Current Simulation Codes

- The user's postprocessing effort is generally linear in the number of runs performed.
- Sharing data between codes is labor-intensive and fragile.
- Users frequently resort to modifying a published code to get what they need.

Why Are These Problems Prevalent?

For most codes:

- single-code postprocessor or none at all
- most output is not compute-ready as far as the user is concerned
- data file protocols are code-specific and fragile

A Solution is Available

The *Self-Describing Data Sets* (SDDS) system provides a common pre- and post-processing system for simulations.

It includes

- a relatively simple but very useful self-describing file protocol
- a toolkit of ~70 general-purpose programs
- additional toolkit of ~20 control-system programs (for EPICS)

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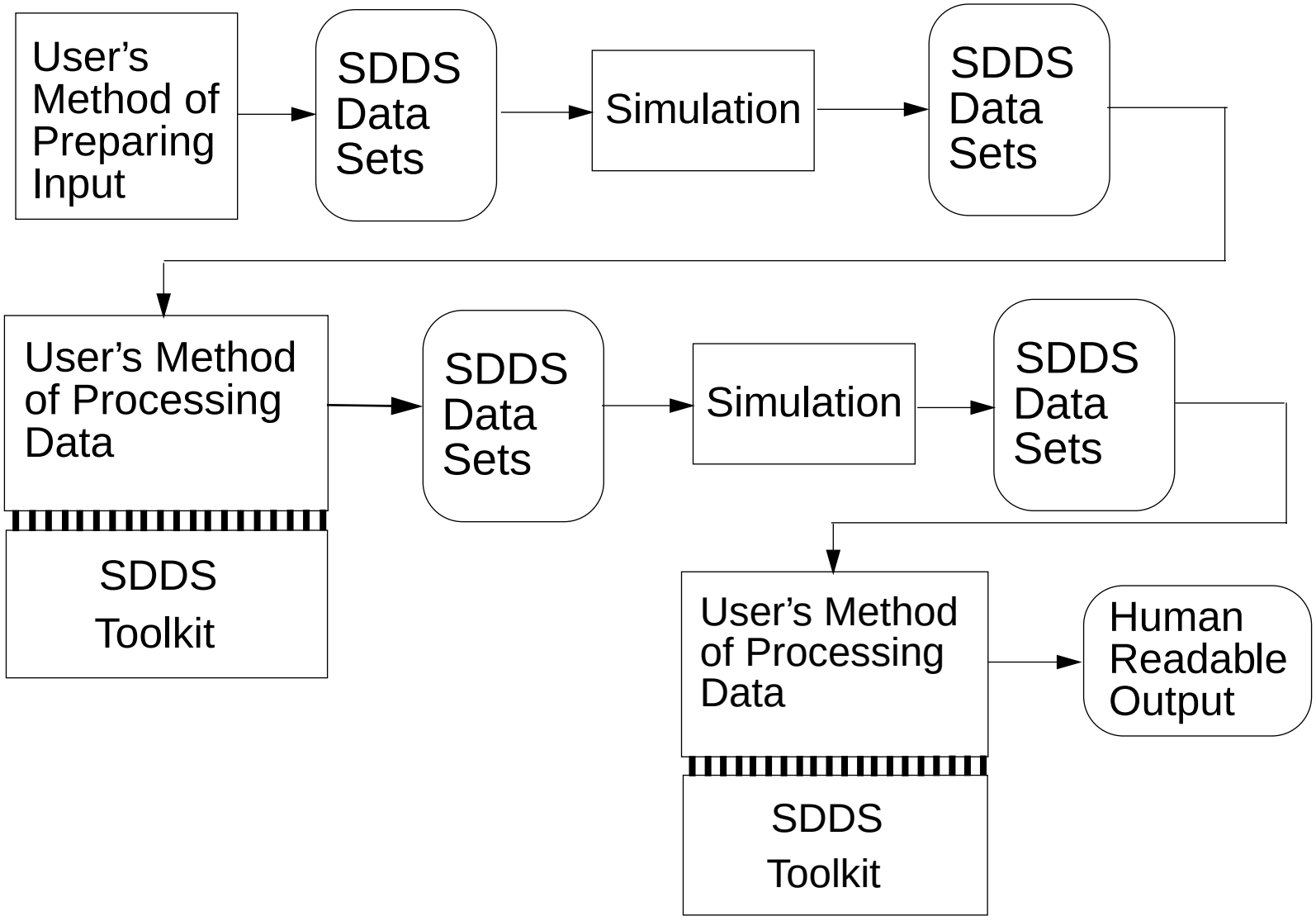
Conceptual Example of SDDS-Linked Simulations



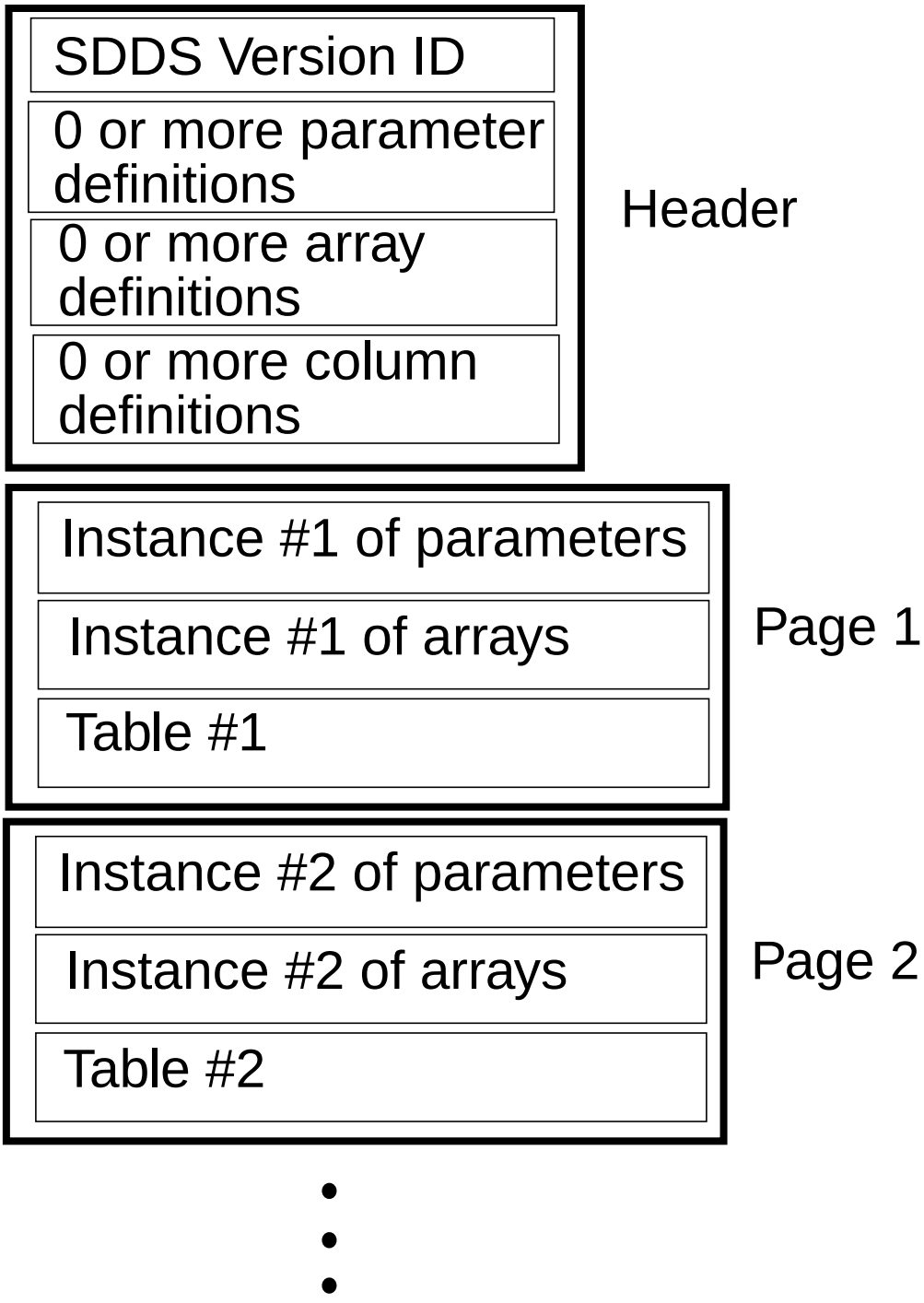
Wide Application of SDDS

- Used for commissioning of APS ring and its injector starting in February 1994. Chosen over MATLAB, IDL, GUS, etc.
- Used for
  - accelerator simulation (14 codes)
  - accelerator high level applications, data logging, data review, etc.
  - experimental data collection and analysis
- SDDS has never caused operational downtime.

SDDS File Protocol

- Data is identified and accessed by name only, using a library of C routines.
- Files include meta-data about data, e.g., units and data type.
- Data may be ASCII or binary.
- No limits on the size or number of data elements.
- Simple data model.

SDDS Data Model



Some Advantages of Using SDDS Files

- Programs can’t be broken by the addition of new data.
- Allows robust input programming.
- Data type flexibility.
- Data is self-documenting.
- Programs can be generic and operate on *named* data.

Program Toolkits

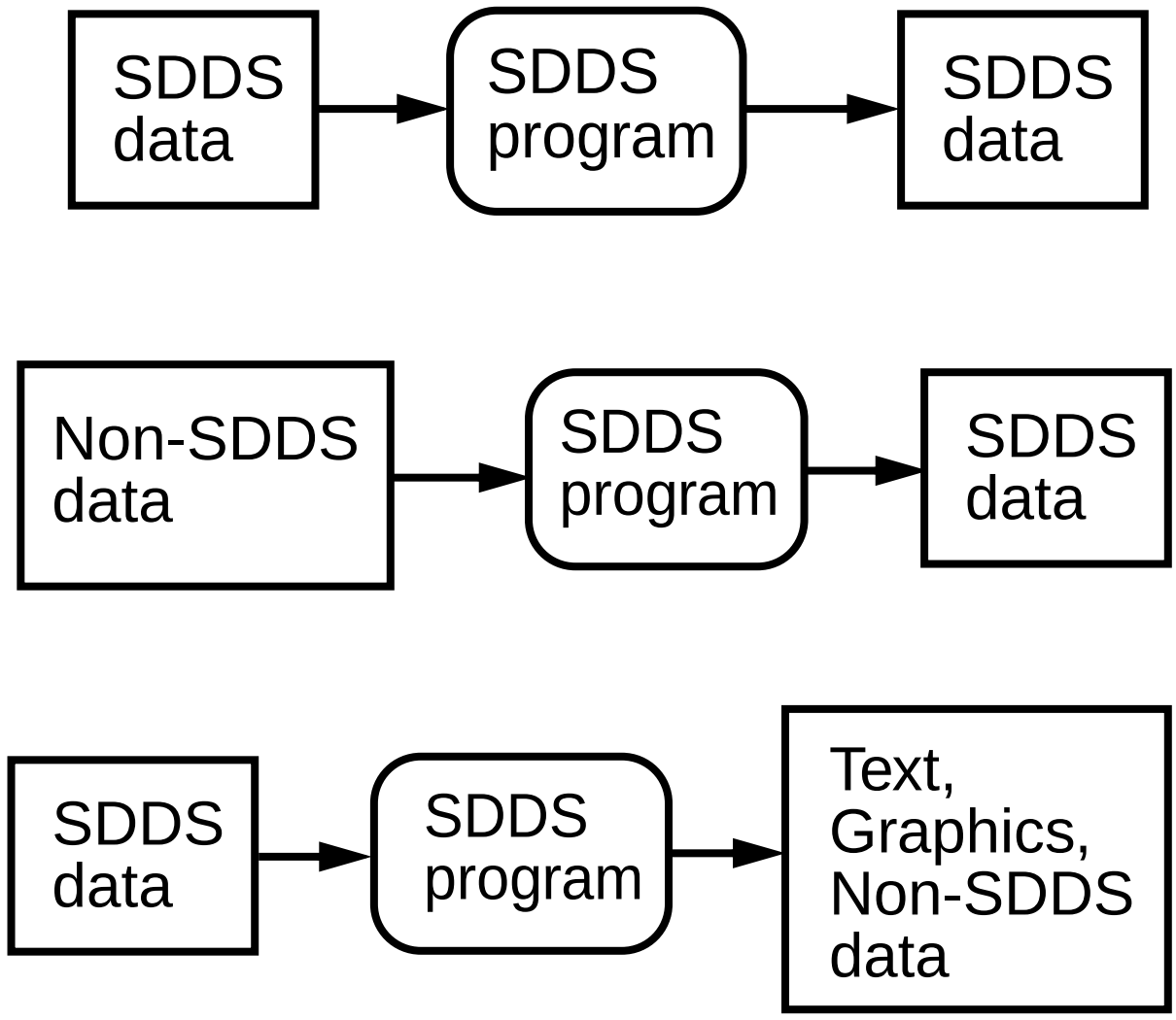
A “toolkit” is a group of programs that can operate on the same type of entity.

- Such programs are generic, configurable, and relatively simple.
- One program’s output is another’s input.
- Decentralized expansion:
  - anyone can add to it independently
  - additions *can’t* break existing tools or applications
- Enhancement doesn’t involve debugging a single, large program.

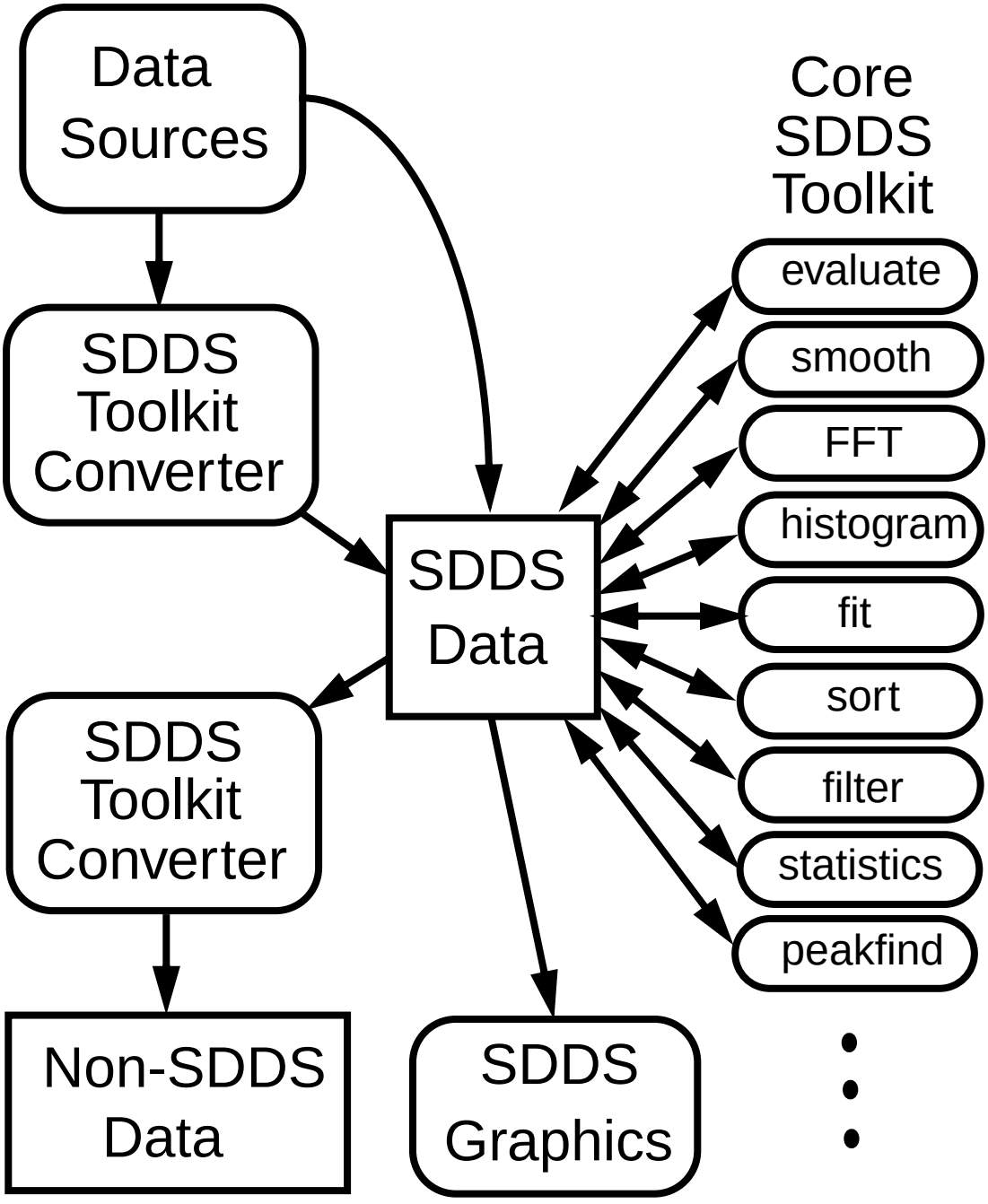
Some SDDS Toolkit Capabilities

- 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, digital filtering, and convolution.
- Smoothing and interpolation.
- Peakfinding.
- Protocol conversion to/from SDDS.
- Text printouts of data.

Three Types of SDDS Toolkit Programs



SDDS Toolkit Paradigm



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SDDS and Programming

- Using SDDS is not like programming.
- For example, to take an FFT of V vs t:

  sddsfft *input output* -column=t,V
  sddsplot -column=f,FFTV *output*

- Take the FFT of BPM00, BPM01,..., BPM99, then compute the mean PSD:

  sddsfft *input* -pipe=out -column=t,BPM?? -psdOutput \
  | sddsrowstats -pipe=in *output* -mean=MeanPSD,PSDBPM??
  sddsplot -column=f,MeanPSD *output*

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- Same, but integrate square-root of PSD vs frequency:

```
sddsfft input -pipe=out -column=t,BPM?? -psdOutput \
| sddsrowstats -pipe  mean=MeanPSD,PSDBPM?? \
| sddsprocess -pipe -define=column,RMSMotion,"MeanPSD sqrt" \
| sddsinteg -pipe=in output -integrate=RMSMotion -versus=f
sddsplot -column=f,RMSMotionInteg output
```

- Find maximum value and its position for each FFT:

```
sddsfft input -pipe=out -column=t,BPM?? \
| sddssmooth -pipe -columns=FFTBPM* -despike \
| sddsprocess -pipe -process=BPM??,max,%sMax \
  -process=BPM??,max,%sPos,functionOf=f,position \
| sddscollapse -pipe \
| sddscollect -pipe=in output -collect=suffix=Max -collect=suffix=Pos
sddsplot -column=Rootname,Max output
```

Scripts

- SDDS tools are command-line driven, so they are scriptable.
  SDDS adds computational muscle to scripts.
- At APS, Tcl/Tk is used for complex work.
- Advantages of using SDDS and scripts
  - an easy way to create and debug complex processing
  - provides a record of what was done
  - effortless repetition of analysis for new data
  - easy modification of previous analysis methods

SDDS-Compliant Simulation Codes

These codes emit only SDDS files, use only SDDS for postprocessing, and also accept SDDS files as input.

- **elegant** — General-purpose accelerator code.[1]
- **shower** — EGS4 wrapper for electron-gamma shower simulation.[2]
- **efield** — Used with shower for multilayer target simulations.[3]
- **clinchor** — Computes coupled bunch growth rates.[2]
- **spiffe** — Fully-electromagnetic PIC code for rf gun simulation.[1]
- **rfgun** — rf gun design code.[1]

1. M. Borland.
2. L. Emery.
3. E. Lessner

Use of SDDS Files by elegant

- Input/output:
  - particle coordinates
- Input:
  - input of data for any element parameter
  - input of impedances and wake functions
  - input of cavity and energy ramps
  - input of kicker waveforms
- Output:
  - turn-by-turn particle data (coordinates or statistics)
  - FFTs of particle motion
  - beam moments vs s
  - transport matrix vs s
  - Twiss parameters vs s
  - lattice parameters (tunes, chromaticities, etc.)
  - coordinates of lost particles
  - initial coordinates of transmitted particles
  - final beam parameters (size, energy, emittance, etc.)
  - amplification factors
  - orbits, corrector strengths, and statistics
  - magnet strengths after tune and chromaticity correction
  - output of internally-generated error data

Use of SDDS Files by spiffe

- Input/output
  - electromagnetic fields
- Input
  - antennae excitation current
  - cathode temporal emission profile
- Output
  - particle coordinates
  - particle snapshots
  - field samples in time and space
  - solenoid fields

Complex Data in a Simple File Protocol

Using “parallel files,” we can store complex data in a relatively simple file protocol. This is why **elegant** and **spiffe** can use SDDS for all of their diverse output.

- Programs create one file for each type of output.
- Usually, related files have similar names.
- Generally, a specific page in one file goes with the same page in all related files.
- Cross-referencing and merging tools are available.

Output-Complaint Codes

These codes write but don't read SDDS files:

- **capture_spc** — Simulation of longitudinal motion with space charge.[1]
- **ABCI*** — Cavity-beam interaction code.[2]
- **TDA3D*** — FEL code.[3]

*APS version.

1. E. Lessner.
2. Y-H Chin. Modified by Y-C Chae.
3. T-M Tran and J. S. Wurtele. Modified by Y-C Chae.

Codes with External Output Conversion to SDDS

- **MAD** — General-purpose accelerator code.[1]
- **MAFIA** — 3D cavity simulation code.[2]
- **ACCSIM** — Tracking code.[3]
- **RACETRACK** — Tracking code.[4]
- **GINGER** — FEL code.[5]

1. H. Grote and F. C. Iselin. TFS to SDDS converter by M. Borland.
2. T. Weiland. MAFIA to SDDS converter by L. Emery.
3. TRIUMF code. Conversion header by Y-C Chae.
4. A. Wrulich. Conversion header by Y-C Chae.
5. W. M. Fawley. Conversion header by Y-C Chae.

Example: Enhacing a Code Using SDDS

- The program **elegant** does canonical tracking, but doesn't provide tune vs $\frac{\Delta P}{P}$.
- With SDDS, we can get this information without modifying the code:
  - prepare input particle coordinates having range of $(\Delta P)/P$ values
  - run **elegant**
  - FFT turn-by-turn x and y coordinates
  - find tunes by finding peaks of FFTs
  - associate tunes with $(\Delta P)/P$ values
- Can also do chromaticity matching from tracking results.

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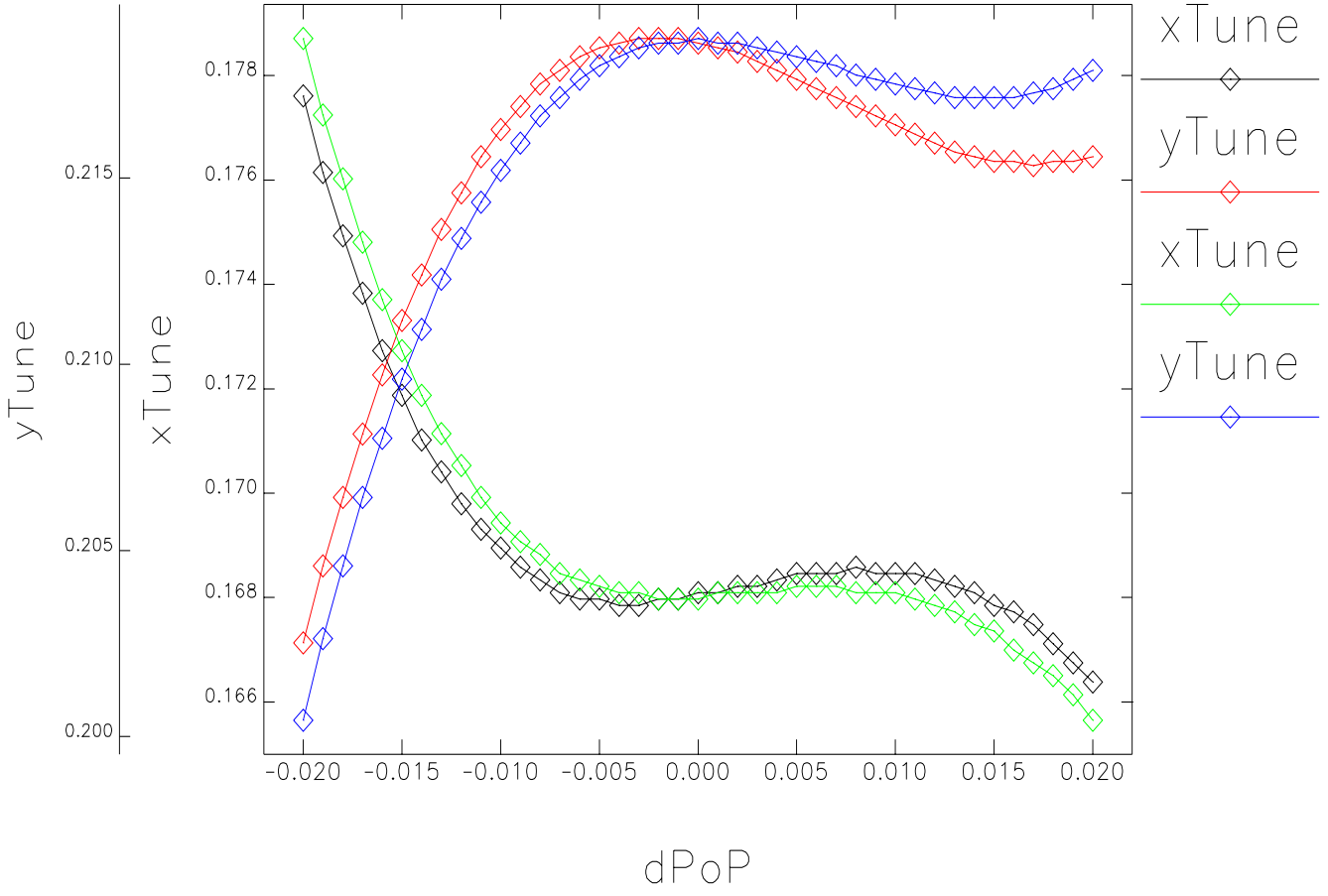

```
#!/bin/csh
# A sample csh script using SDDS tools to find tune variation
# with energy from turn-by-turn tracking data.

# Make input particles with dP/P from -0.02 to 0.02,
# one particle per SDDS page.
sddssequence -pipe=out -define=dPoP0,type=double \
  -sequence=begin=-0.02,end=0.02,delta=0.001 \
  | sddsbreak -pipe -rowlimit=1 \
  | sddsprocess -pipe=in "-define=column,p,880 dPoP0 1 + *" \
  -define=column,t,0,units=s -define=column,xp,0 -define=column,yp,0 \
  -define=column,x,0,units=m -define=column,y,0,units=m \
  -define=parameter,dPoP,dPoP0 \
  par.input

elegant par.ele    # track the particles

# FFT the turn-by-turn data
# associate with the dP/P value from file made above
# find the locations of the peaks (=tunes)
sddsfft par.turnByTurn -pipe=out -column=Pass,x,y \
  -suppressAverage -window=Hanning \
  | sddsxref -pipe par.input -transfer=parameter,dPoP -leave=* \
  | sddsprocess -pipe \
  -process=FFTx,max,xTune,functionOf=f,position \
  -process=FFTy,max,yTune,functionOf=f,position \
  | sddscollapse -pipe=in par.tune
# Plot the results
sddsplot -column=dPoP,?Tune par.tune -yScales=names \
   -graph=symbol,vary=subtype,scale=2,connect=subtype -legend
```

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Example: Postprocessing 1000 Runs

- Want PAR lattice functions with
  - magnet alignment and strength errors
  - orbit, tune, and chromaticity correction
- Using 20 separate workstations, 1000 random sets takes ~15 minutes.
- An SDDS-based script does all data analysis and display.
- Easy to repeat for a new lattice.
- Similar applications:
  - dynamic aperture
  - injection efficiency

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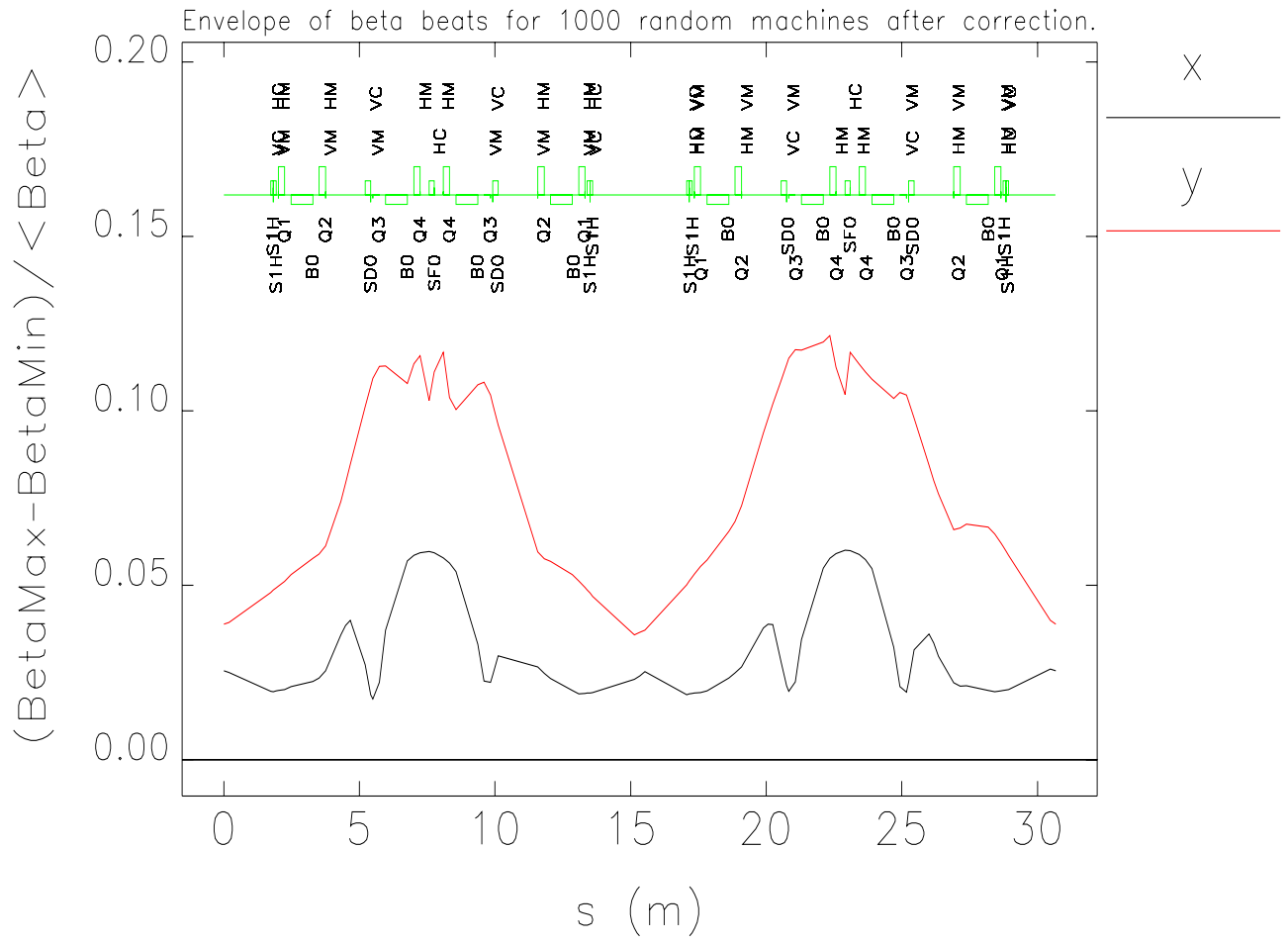
Beta beat for 1000 Random Machines



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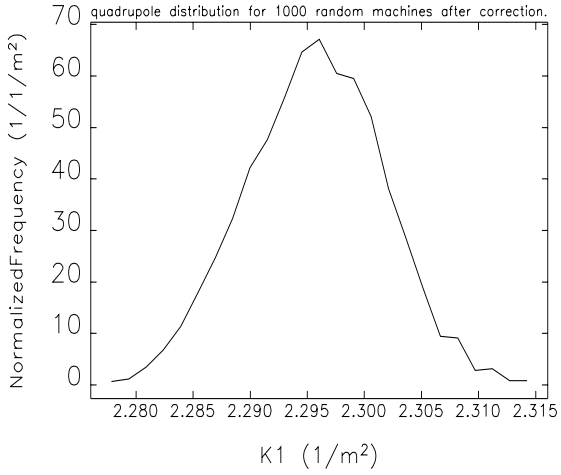
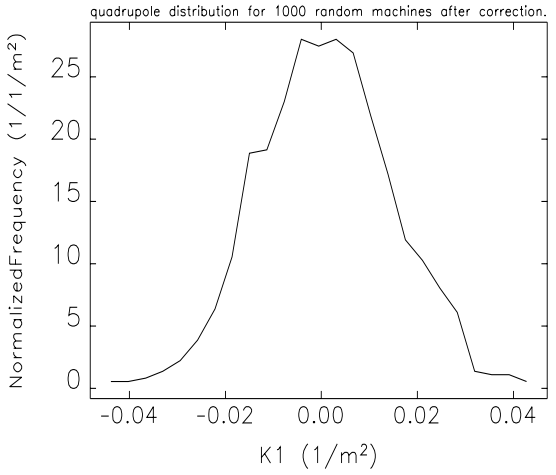
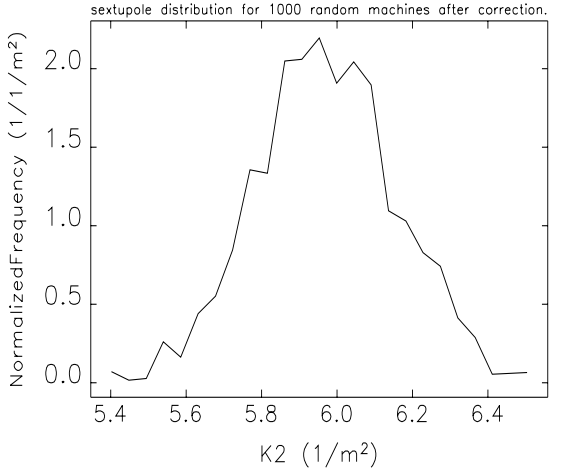
Statistics of Quads and Sexts for 1000 Machines



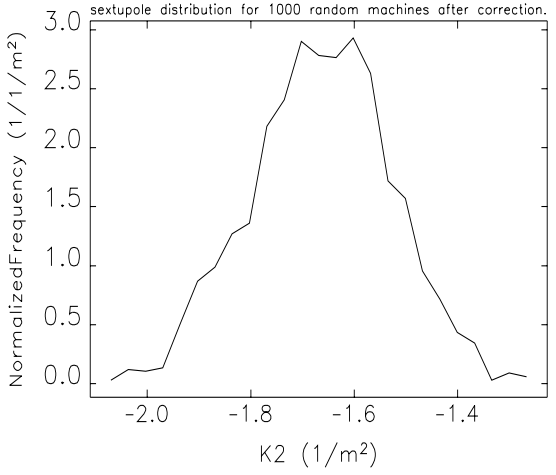
Q2 statistics Mean: 2.296 StDev: 0.006



Q3 statistics Mean: 0.001 StDev: 0.014



Mean: 5.970 StDev: 0.186



Mean: -1.664 StDev: 0.135

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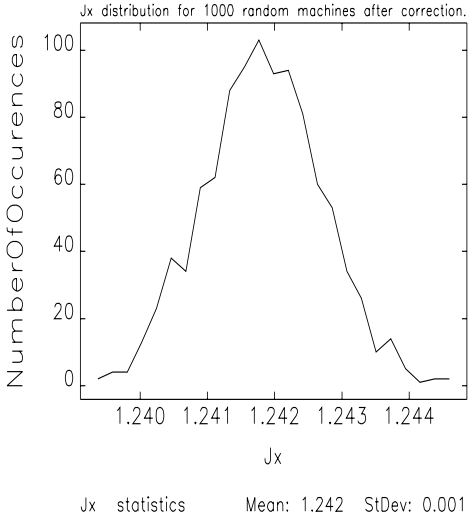
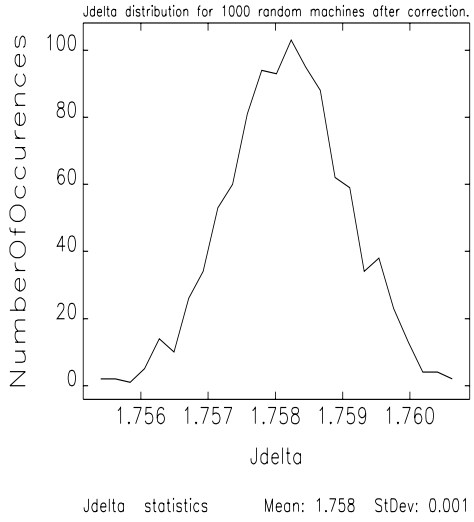
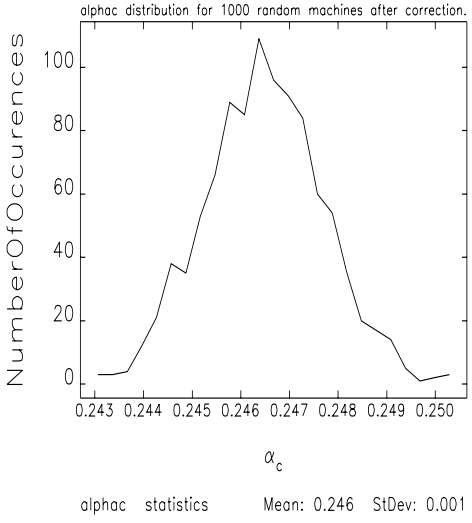
Statistics of Some Global Parameters for 1000 Machines



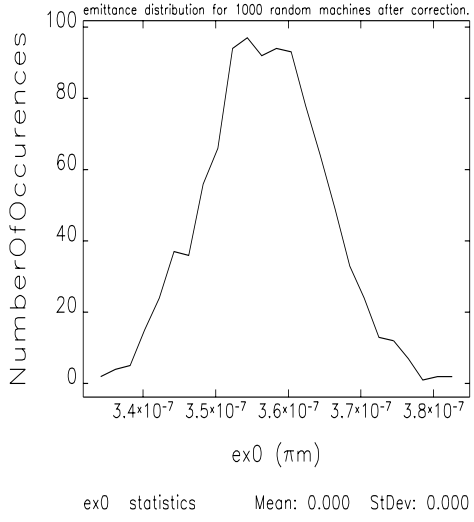
Jx statistics Mean: 1.242 StDev: 0.001



Jdelta statistics Mean: 1.758 StDev: 0.001



alphac statistics Mean: 0.246 StDev: 0.001



ex0 statistics Mean: 0.000 StDev: 0.000

Multi-Code Simulations Using SDDS

- **shower** and **efield:** multilayer positron target for slow positron production.[1]
- **spiffe** and **elegant:** design and optimization of APS rf gun, transport line, and linac.[2]
- **shower** and **elegant*:*** positron emission and capture in APS linac.
- **shower** and **elegant:** effects of window on injected beam losses**.**

1. M. White and E. Lessner, “Slow Positron Target Concepts for the APS Linear Accelerator,” Proc. 11th International Conf. on Positron Annihilation, Material Sciences Forum Volumes 255-257, pp. 778-780 (1997).
2. M. Borland, “An Improved Thermionic Microwave Gun and Emittance-Preserving Transport Line”, Proc 1993 PAC, pp 3015-3017. Also J. Lewellen, private communication.

Top-Up Safety Tracking

- Top-up operation, wherein beam is injected with shutters open, is a high-priority goal at APS.
- Issue:
  Assuming a partial dipole short, can beam be extracted down a photon beamline during injection while keeping stored beam?
- Approach:
  Evaluate survival of stored beam and escape of injected beam for various fault scenarios.
- Work of M. Borland and L. Emery for APS top-up safety review.

—Overview of Top-Up Simulations—

- Each aperture configuration requires 542 runs of **elegant**.
- 12 groups of runs simulate different failure scenarios.
- Use ~20 workstations, taking ~2 days.
- Tcl scripts set up the runs. Most runs are
  - set up from templates
  - configured using SDDS files, often from another **elegant** run in the set

Top-up Tracking Setup Data

- Match 22 different integer tunes for APS. Quad settings are saved as SDDS files.
- For selected lattices, find stable range of variation for a single quadrupole of each family and save the data in SDDS files.
- Generate acceptance-filling phase-space distributions for two types of photon beamline and save as SDDS files.
- Use SDDS toolkit to create 2D field maps for quadrupoles and sextupoles from PE2D simulation output.

Top-Up Simulation —Stored Beam Survival—

- Compute closed orbit for various lattices and various fault conditions. Evaluate beam survival with:
  - dipole strength error,
  - plus single quadrupole errors within the stable range of tunes,
  - plus single quadrupole having a maximally dangerous dipole field due to a short.
- SDDS files used for magnet strengths and quadrupole error range.
- For each scenario, find dipole strength error at which beam at which beam no longer survives.

Top-Up Simulation —Photon Beamline Tracking—

- Track backwards down photon beamlines with conditions corresponding to the matching closed orbit simulation.
- SDDS used for
  - reading data computed during the stored beam simulations. For example, may load quadrupole strength and dipole kick values.
  - input particle distributions from previous tracking in photon beamlines.
  - field maps of quadrupoles and sextupoles giving fields at large x.
- For each scenario, find the dipole strength error at which no beam exits the sector.

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Top-Up Simulation —Postprocessing—

- There is no manual data gathering or calculation required.
- A postprocessing script using the SDDS toolkit is used for each group of simulations. These may be used individually to review results.
- Another script runs the group scripts to produce final results.
- From 130MB of data, we get a *single number* and a *one-word message* that tells us if top-up is safe under the simulated conditions, e.g.:

```
Minimum FSE gap: 0.0502   Safe!
```

- An SDDS file is also produced with more detailed summary data.

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Conclusion

- The SDDS data file protocol is suitable for use with diverse codes.
- The SDDS toolkit provides powerful, general pre- and post-processing for diverse codes.
- Advantages of this approach:
  - scriptable pre- and post-processing for compliant codes
  - combined use of codes is easy
  - allows highly complex, automated use and extension of codes