MADX-UAL SUITE FOR OFF-LINE ACCELERATOR DESIGN AND SIMULATION*

N. Malitsky#, R. Fliller III, F. Pilat, V. Ptitsyn, S. Tepikian, J.Wei, BNL, Upton, NY 11973
F.Schmidt, CERN, Geneva, Switzerland
R.Talman, Cornell University, Ithaca, NY 14853, USA

Abstract

We present here an accelerator modeling suite that integrates the capability of MAD-X and UAL packages, based on the Standard eXchange Format (SXF) interface. The resulting environment introduces a collection of accelerator applications ranging from the lattice design to complex beam dynamics studies. The extended capabilities of the MADX-UAL integrated approach have been tested and effectively used in two accelerator projects: RHIC, where direct comparison of operational and simulation data is possible, and the SNS Accumulator Ring, still in its design phase.

RATIONALE

An accelerator is a complex scientific and engineering device encompassing many heterogeneous systems. Often, the effect of each system can be estimated or simulated by small applications. However, a growing pile of independent programs with overlapping functionalities and inconsistent sets of input and output parameters eventually forces accelerator physicists to develop or look for some integrated toolkit. Moreover, stringent parameters of modern high-intensity machines impose new expectations on beam dynamics studies and usually require simultaneous analysis of several physical effects and processes.

In this paper, we consider a composite approach addressing both the design and simulation applications. The approach is based on the MAD design toolkit and the UAL simulation environment, which has been successfully used in the design of RHIC and SNS projects. Originally, the UAL model was initialized directly from the MAD-8 file. However, because of the differences in program architectures, the MAD8-UAL interface was limited, supporting only a subset of the MAD input language. The new MAD-X version diminished this gap by providing the additional interface based on the Standard Exchange Format (SXF). The resulting suite has been applied to the analysis of RHIC operational data and proposed as a prototype of the off-line simulation facility. The next sections will give a brief overview of the suite components and its future extension based on the ROOT analysis toolkit.

MAD-X

MAD-X [1] is the successor of MAD 8, a very popular program used in the design of most existing accelerators. The long history (more than 15 years) of the MAD project has led to a considerable list of various applications that helped to validate, correct, and select the most effective approaches and algorithms in accelerator physics. Over time however, the initial structure grew too complex and eventually became an obstacle for future upgrades. As a result, the MAD-X effort was started to resolve this dilemma by upgrading MAD 8 components based on a new program organization. Below is a list of the main principles of the MAD-X architecture:

- The program consists of a core part and attachable modules (such as optics calculation, matching, etc); the core provides data structures for these modules, handles all commands, and controls the program execution.
- The core low level structures and functions are written in the C programming language, replacing the Zebra-based memory management.
- The modules can be in any languages linking with C.

This highly modular and flexible organization not only facilitated the adaptation of existing MAD-8 Fortran 77 components, but also opened a door for new upgrades. One of the most important extensions is the interface to the Polymorphic Tracking Code (PTC[2]) of E. Forest. PTC is written in the object-oriented Fortran 90 and brings symplectic exact integrators, Taylor maps, Normal Form techniques, and other important features.

UAL

The Unified Accelerator Libraries (UAL[3][4]) environment focuses on the complex simulation tasks of modern beam dynamics studies. It extends and compliments the MAD-X design toolkit with an open catalog of collaborative tracking algorithms and a consistent mechanism for building configurable project-specific accelerator off-line models. As part of this mechanism, UAL introduces a special Accelerator Propagator Description Format (APDF) for associating tracking algorithms with accelerator sectors and individual elements. The following file, for example, describes the tracking engine of the Model Independent Analysis (MIA) application built from TEAPOT, TIBETAN, and BPM propagators:

```
<propagator>
  <link algorithm=”TEAPOT::DriftTracker” types = “Default” />
  <link algorithm=”TEAPOT::DipoleTracker” types=”SBend” />
  <link algorithm=”TEAPOT::MltTracker”
        types=”Quadrupole|Sextupole|Multipole|[VH]kicker|Kicker” />
  <link algorithm=”TIBETAN::RfCavityTracker” types=”RFCavity” />
  <link algorithm=”MIA::BPM” types=”Monitor” />
</propagator>
```

*Work performed under the auspices of the U.S. Department of Energy.
#malitsky@bnl.gov

The APDF-based approach addresses a broad spectrum of applications ranging from online models with a few efficient integrators to off-line full-scale realistic beam dynamics studies including several physical effects and processes. At this time, the UAL catalog of algorithms encompasses non-linear symplectic trackers, differential and Lie algebra, space-charge effects, transverse impedance model, collimator, and diagnostics devices.

MAD-UAL INTERFACE

The MAD-UAL interface was introduced in 1998 as a part of the US-LHC collaboration effort. The interface was based on the Standard Exchange Format (SXF[5]) providing a uniform fully-instantiated description of the accelerator state. Technically, the SXF structure has been designed after merging two concepts: the MAD sequence of accelerator elements and the UAL normalized sets of element attributes (such as measured field harmonics, alignment errors, apertures, etc.) Here is an example of the SXF quadrupole with measured field errors:

```
yi6-qd2
 quadrupole {
    tag = q2i6
    at = 30.1731759666
    l = 3.391633
    n = 2
    body = {
      kl = [ 0 -0.190560799172 ]
    }
    body.dev = {
      kl = [ 0 0 -6.3e-05 -0.005974 -0.957321 ]
      kls = [ 0 0 0.000615 -0.017347 0.827759 ]
    }
};
```

A more detailed description of the SXF specification can be found in [5]. To facilitate the exchange of the SXF files among accelerator codes, special attention was given to the simplicity of the grammar and its compatibility with existing parsing techniques. Thus the grammar was expressed in the Backus-Naur Form (BNF) and implemented with the standard Lex/Yacc software. The SXF parser has been developed as a generic library of the C++ classes adaptable to different accelerator codes.

Later, to provide extensibility, the SXF specification was enhanced and transformed into the new proposal: Accelerator Description Exchange Format (ADXF[6]) based on the XML industrial standard. In ADXF, the same quadrupole with measured field errors would be described as:

```
<quadrupole id = "yi6-qd2" design="q2i6" at=" 30.1731759666 ">
  <attributes>
    <frame l="3.391633" n="2" />
    <mfield
      l = "3.391633"
       kl ="[ 0,  -0.190560799172  , -6.3e-05, -0.005974, -0.957321 ]"
      knl =" [ 0, 0, 0.000615, -0.017347, 0.827759 ]"
    />
  </attributes>
</quadrupole>
```

A comparison of these two examples shows that conversion from SXF to ADXF is very straightforward. But before its implementation, we plan to modify the ADXF specification to meet the new requirements introduced by the PTC, which recently became a part of the MAD-X toolkit.

EVOLUTION OF MAD-UAL APPLICATIONS

The first applications of the MAD-UAL approach were driven by the US-LHC tasks. The primary interest was the employment of the UAL open programming environment for developing new project-specific algorithms and extensions. For example, it was used for studying various commissioning correction algorithms in the presence of alignment and field errors [7].

Later, the composite design-simulation environment was applied to the SNS accumulator ring project. The design of linear optics and sextupole correction was done with the MAD 8 toolkit and the UAL simulation environment [8] hosted the accurate beam loss model based on the detailed beam dynamics studies including the following topics:

- nonlinear effects arising from kinematic terms, magnet imperfections, and fringe fields;
- dynamic aperture and diffusion map studies;
- optimization of injection painting schemes;
- effect of space charge during transverse painting;
- tune spread due to space charge, chromaticity and other nonlinearities in combination;
- choice of working point dictated by imperfection resonance crossing in the presence of space charge;
- half-integer coherent resonance crossing;
- collective instability due to transverse coupling impedance;
- halo development and beam loss modeling.

After the MAD-X Day which officially introduced the MAD-X project, the BNL team started the gradual upgrade of the accelerator off-line software. Eventually, the overall effort was transformed to the new challenging project: RHIC off-line model aiming to facilitate analysis of accelerator problems and benchmarking of theoretical algorithms with experimental data. The overall off-line facility is presented on Figure 1.

The facility is built from three major components: MAD-X, UAL, and ROOT. The MAD-X toolkit deals with all design issues associated with changes of lattice optics, such as beta squeeze, upgrade of interaction regions, etc. The various simulation applications are based on the UAL framework and open catalog of tracking algorithms. Finally, the ROOT toolkit [9] facilitates the visualization of simulation results. We consider two categories of post-processing visualization applications: instrumentation displays and accelerator physics (AP) graphics. Instrumentation displays aim to facilitate the comparison of simulation results with operational data; the AP visualization graphics provide additional information for diagnosing problems and investigating mismatches between the off-line model and the accelerator.

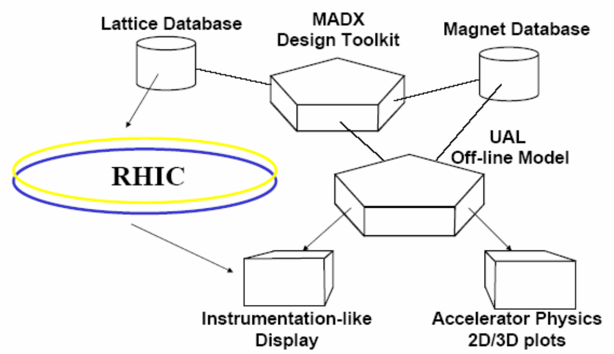

Figure 1: RHIC off-line simulation facility.

The functionality of this facility can be illustrated by benchmarking the RHIC non-linear model with beam experiments. One of these was dedicated to the analysis of the RHIC operational non-linear IR correction. The scheme was based on local orbit bumps centered on IR triplets. The associated control application [10] measured tune shifts as a function of bump amplitudes and consequently extracted sextupole and octupole coefficients from a resulting curve. A typical plot on the IR bump application is shown on Figure 2.

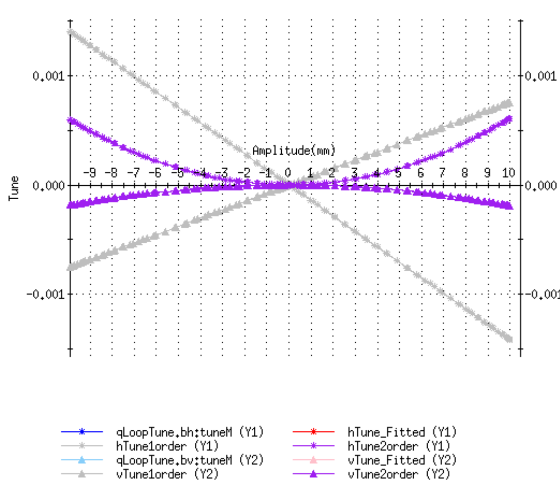

Figure 2: IR bump fitted plots of sextupole and octupole tune shifts vs bump amplitude.

The corresponding off-line application started with the MAD-X toolkit producing the SXF file with the current linear optics. After adding measured field errors, the final SXF file was delegated to the UAL-based simulation environment. To implement the bump scenario, part of the control program was connected with the off-line model. The composite application correctly reproduced the tune shifts of known non-linear correctors, but disagreed with the measured data induced by IR field errors. For identifying this discrepancy, we added the ROOT-based tune shift budget plot showing the contributions of individual non-linear elements:

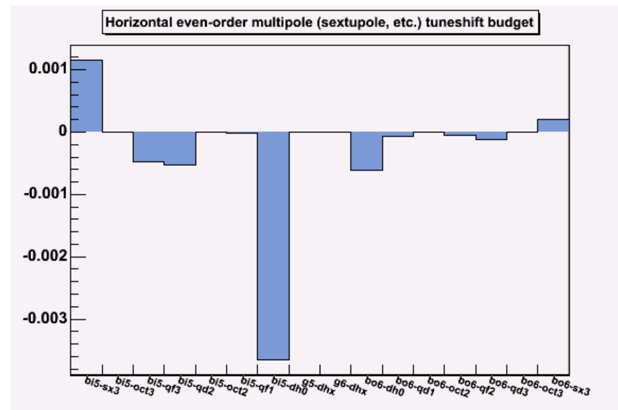

Figure 3: Tune shift budget plot.

In our terminology, this plot would be in the category of AP graphics aiming to explain instrumentation results. The plot clearly points on the dh0 magnets, whose sextupole harmonics will be analyzed before the next RHIC run. The facility-based procedure is considered as a prototype for further beam experiment studies.

REFERENCES

[1] http://frs.home.cern.ch/frs/Xdoc/Introduction/doc.html

[2] E.Forest, F.Schmidt, E.McIntosh. *Introduction to the Polymorphic Tracking Code*. KEK Report 2002-3 (2002)

[3] N. Malitsky and R.Talman, *Unified Accelerator Libraries*, AIP 391 (1996)

[4] http://www.ual.bnl.gov

[5] H. Grote, J. Holt, N. Malitsky, F. Pilat, R. Talman, C.G. Trahern. *SXF (Standard eXchange Format): definition, syntax, examples*. RHIC/AP/155 (1998)

[6] N.Malitsky and R.Talman. *Accelerator Description Exchange Format*, ICAP98 (1998)

[7] W.Fisher, F.Pilat, V.Ptitsin. *The Application of the SXF Lattice Description and the UAL Software Environment to the Analysis of the LHC*, PAC99 (1999)

[8] N.Malitsky, P.Cameron, A.Fedotov, J.Smith, J.Wei. *Development and Applications of the UAL-based SNS Ring Simulation Environment*, EPAC02 (2002)

[9] R.Brun and F.Rademakers. *ROOT - An Object Oriented Data Analysis Framework*, Nucl. Instr. & Meth. In Phys. Res. A 389 (1997). See also http://rott.cern.ch

[10] S. Binello, private communication