Update on OPAL V.1.4.0

A. Adelmann, for the OPAL developer team:
A. Gsell, M. Frey (PSI), T. Kaman (UZH), Ch. Kraus (HZB), Y. Ineichen (IBM), S. Russell, X. Pang (LANL), Ch. Wang, J. Yang (CIAE), D. Winklehner (MIT), Ch. Rogers, S. Sheehy (Rutherford)

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Outline

1. OPAL in a Nutshell
2. New Features in OPAL
3. Future plans
OPAL is an open-source tool for charged-particle optics in large accelerator structures and beam lines including 3D space charge, particle matter interaction and multi-objective optimisation.

- OPAL is built from the ground up as a parallel application
- OPAL runs on your laptop as well as on the largest HPC clusters
- OPAL uses the MAD language with extensions
- OPAL is written in C++, uses design patterns, easy to extend
- Regression tests are running on every git change
- Webpage: https://amas.psi.ch/OPAL
- OPAL Discussion Forum: https://lists.web.psi.ch/mailman/listinfo/opal
- International team of 13 developers & Ø(40) users
OPAL is designed for 4 flavours:

1. **OPAL-T**
   - time as the independent variable
   - capable to build S2E models (**beamlines**, rf-guns, linac)
   - auto-phasing, wake fields, 1D CSR
   - 3D space charge & particle matter interaction
   - field emission (dark current studies), multipactoring capabilities
   - from e, p to Uranium (q/m is a parameter)

2. **OPAL-CYCL** [Y. Bi, et al., PR-STAB 14(5) (2011)],

   [J. Yang, et al., NIM-A 704(11) (2013)]
   - neighbouring turns [J. Yang, et al., PR-STAB 13(6) (2010)]
   - time integration, 4th-order RK, LF, adaptive schemes
   - single particle tracking mode & tune calculation
   - find matched distributions with linear space charge

3. **OPAL-ENVELOPE** (**not yet released**)

4. **OPAL-MAP** (**not yet released**)
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1. OPAL in a Nutshell

2. New Features in OPAL
   - Fieldsolver (AA PSI)
   - Cyclotron Tracker (D. Winklehner MIT & A. Gsell PSI)
   - Time Dependent Fields (Ch. Rogers ASTeC)
   - Binary Distribution (A. Gsell PSI)
   - GPU Support (PhD. project U. Locans PSI/Univ. Latvia)
   - Matched Distribution (Ch. Baumgarten, M. Frey & AA PSI)

3. Future plans
3D space-charge calculation in OPAL
AA (PSI)

The space-charge forces are calculated by solving the electrostatic 3D Poisson equation.

- **FFT (default):** with open boundary conditions using a standard or integrated Green function method
- **FFT is GPU accelerated** NEW
- **SAAMG-PCG:** iterative solvers that takes into account
  [AA et al., JCP, 229 12 (2010)]
  - simple domains such a cylinder with an elliptic area
  - complicated, irregular domains **NEW**
  - default since version 1.4.0
Complex Geometry in Action

D. Winklehner MIT & A. Gsell PSI
Changes to OPAL-cycl 1

D. Winklehner MIT & A. Gsell PSI

- Capability to include the central region of a compact cyclotron.
- Generalization of reference coordinate system from 2D to 3D.
- Loading of a mesh containing the geometry data.
  This is important for:
  1. particle termination
  2. boundary conditions within the iterative field solver
- Support for geometries with several disconnected surfaces
Time Dependent RF-Fields

Ch. Rogers (ASTeC)

This is all within the *Ring* definition:

- A field map routine to calculate the RF field at $x, y, z, t$
- The ability to enable overlapping field maps
- A user interface to enable displacement and rotation of field maps
  - enable drift (field free) regions

```plaintext
rf_f0 = 0.0028583;  // GHz
rf_f1 = 9.80429e-09;
rf_f2 = -3.204e-14;
rf_f3 = -4.69392e-21;
phi = 2.*PI*0.365;

rf_frequency: POLYNOMIAL_TIME_DEPENDENCE, P0=rf_f0, P1=...;
rf_amplitude: POLYNOMIAL_TIME_DEPENDENCE, P0=1.;
rf_phase:    POLYNOMIAL_TIMEDEPENDENCE, P0=phi;
```
rf_cavity: VARIABLE_RF_CAVITY,
PHASE_MODEL="rf_phase",
AMPLITUDE_MODEL="rf_amplitude",
FREQUENCY_MODEL="rf_frequency", ... ;

triplet: SBEND3D, FMAPFN="fdf-tosca-field-map.table", ... ;
ringdef: RINGDEFINITION, HARMONIC_NUMBER=1,
        LATTICE_RINIT=2350.0, LATTICE_PHIINIT=0.0, ...
        BEAM_RINIT=x_closed_orbit, SYMMETRY=1.0;

l1: Line = (ring, probe1, triplet, triplet, triplet,
          triplet, triplet, triplet, triplet,
          cavity_offset, rf_cavity);
...
Time Dependent RF-Fields cont.
Ch. Rogers (ASTeC)

- Run with fixed frequency
  - rf_frequency: POLYNOMIAL_TIME_DEPENDENCE, P0=rf_f0;
- Particles track through stationary bucket for 1000 turns (ERIT)
Now vary the rf frequency
- rf_frequency: POLYNOMIAL_TIME_DEPENDENCE, P0=rf_f0, P1=rf_f1, P2=rf_f2, P3=rf_f3;

See particles accelerating
- Small distortions due to variation in frequency

Precise FFAG simulations with 3D space charge possible
Time Dependent RF-Fields cont.
Ch. Rogers (ASTeC)

- Now vary the rf frequency
  - rf_frequency: POLYNOMIAL TIME DEPENDENCE, P0=rf_f0, P1=rf_f1, P2=rf_f2, P3=rf_f3;
- See particles accelerating
  - Small distortions due to variation in frequency

Precise FFAG simulations with 3D space charge possible
Building OPAL in non trivial, hence we provide pre-build binaries

- for Linux and Mac OS X
- the distribution includes everything to run OPAL and tools ...

Easy installation procedure

1. download from the OPAL webpage
2. choose an installation directory \$DIR and change to this directory
3. unpack with `tar xvf OPAL-VERSION-XXX.tar.bz2`
4. setup your environment source
   \$DIR/OPAL-VERSION/etc/profile.d/opal.sh
GPU Support

GPU Support (PhD. project U. Locans PSI/Univ. Latvia)

Dynamic Kernel Scheduler (DKS) [AA, U. Locans, A. Suter (2016)] is a slim software layer between host application and hardware accelerator.

Heterogeneous hardware

Heterogeneous software

Update on OPAL V.1.4.0
GPU Support II
GPU Support (PhD. project U. Locans PSI/Univ. Latvia)

**DKS concept**

- **Communication:** common interface to communicate with different types of devices hiding all the details of different frameworks used for each device.
- **Function library:** library of predefined algorithms written using CUDA, OpenCL, OpenMP.
- **Auto-tuning:** based on the system setup and executable tasks select appropriate implementation and configuration to execute the code (not yet available).
Monte Carlo Computation on HW Accelerators

- A degrader is a slab of matter (incl. gas) with a thickness adjusted to the amount of energy to be lost
- Energy loss: using Bethe-Bloch
- Scattering: including Multiple Coulomb Scattering and large angle Rutherford Scattering
Monte Carlo Computation on HW Accelerators

**Example:** OPAL 1cm thick graphite degrader example.  
**Host code:** 2x Intel Xeon Processor E5-2609 v2  
**Accelerator:** Nvidia Tesla K20, K40 or Intel Xeon Phi 5110p

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</tbody>
</table>
Matched Distribution with Linear Space Charge
Ch. Baumgarten, M. Frey & AA (PSI)

- **Goal:** Find a stationary distribution $\sigma$, i.e.
  \[
  \sigma(s + L) = M\sigma(s)M^T
  \]
  \[
  \sigma = \sigma(s + L) \overset{!}{=} \sigma(s)
  \]
  with linear transfer map $M$.

- **Assumptions:**
  - azimuthal symmetry
  - coasting beam
  - isochronicity

- **Input:** energy, emittances, intensity, field map

- **Additional Output ClosedOrbitFinder:**
  - radial and vertical tune
  - field index
  - orbit radius
  - radial momenta

THC02 - Matched Distributions with Linear and Non-Linear Space Charge, M. Frey
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   - Adaptive Mesh Refinement (AMR) Solver
   - OPAL-\texttt{T-3d}
   - Multiobjective Optimiser
Adaptive Mesh Refinement (AMR) Solver
PhD. Project M. Frey (PSI), T. Kaman (UZH), A. Almgreen (LBNL) & AA

- efficient and precise iterative solver with multi-scale capabilities
- BoxLib an AMR software framework (LBNL)
- More efficient and accurate space-charge calculation
- Heterogeneous problem with respect to the spatial discretization: only small areas of interest require a fine resolution
**OPAL-T-3d**

Towards fully 3D, work in progress, lead by Ch. Metzger (HZB)

- Elements in input file placed along design path (ELEMEDGE)
- Is simple for user and works fine for straight machines

**Major drawbacks for dipoles:**

- no overlap between dipole field and field of any other element
- misalignment is problematic

**Solution:** place elements in 3D space.
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OPAL-T-3d \textdagger
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For ERL bERLinPro
- include all elements only once although traversed twice ($n \times$)
- add apertures to all elements
- add origin and initial orientation of beamline (elements)
- IPAC 16 paper : WEPOY034 Latest Improvements of OPAL

Curtesy of Ch. Metzger (HZB)
Multiobjective Optimiser

Dynamic Kernel Scheduler

- MAD-Parser
- Flavors: t, Cycl, Envelope, Map
- SC Solvers: FFT & SAAMG-PCG
- P³M & AMR
- Distributions
- Autophasing
- 1D Wake Fields
- Particle Emission
- Particle Matter Interaction
- DKS API

- cuFFT
- cuBLAS
- CUDA
- cuFFT
- cuBLAS
- OpenMP
- Offload
- MIC
- Intel MKL
- Intel TBB

-Multi Objective Optimizer
- Genetic Optimizer, NSGA2 & PISA

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References I