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)

CYCLOTRONS 2016 Zürich 14. September

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`
- Manual: `http://amas.web.psi.ch/docs/opal/opal_user_guide.pdf`
- OPAL Discussion Forum: `https://lists.web.psi.ch/mailman/listinfo/opal`
- International team of 13 developers & $\mathcal{O}(40)$ 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), multipacting 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 [M. Toggweiler, AA, et al. (2014)]
     - 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

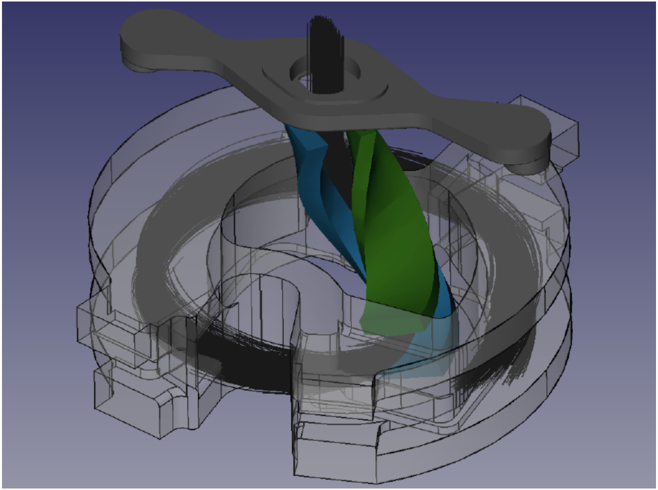
AA (PSI)

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

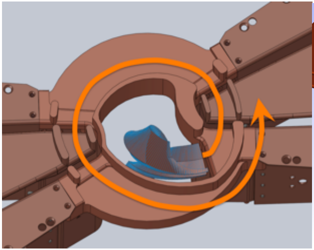
D. Winklehner MIT & A. Gsell PSI

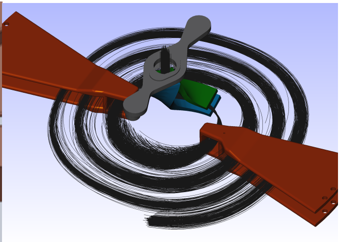


Changes to OPAL-cycl I

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

```
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_TIME_DEPENDENCE, P0=phi;
```

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Time Dependent RF-Fields cont.

Ch. Rogers (ASTeC)

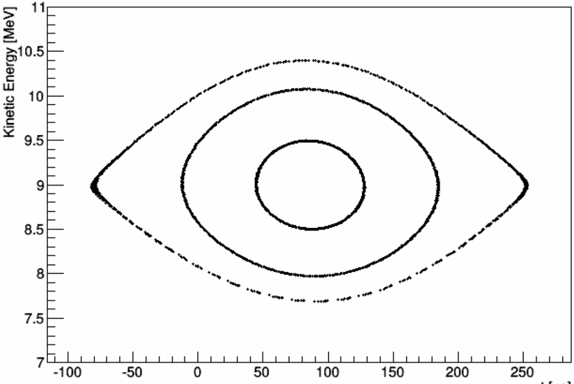
```
rf_cavity: VARIABLE_RF_CAVITY,
PHASE_MODEL="rf_phase",
AMPLITUDE_MODEL="rf_amplitude",
FREQUENCY_MODEL="rf_frequency", ... ;

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, triplet,
cavity_offset, rf_cavity);
...
```

PAUL SCHERRER INSTITUT PSI

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)



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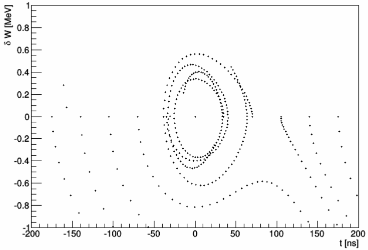
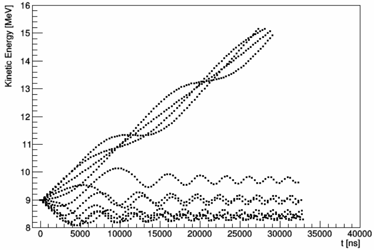
Time Dependent RF-Fields cont.

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

Time Dependent RF-Fields cont.

Ch. Rogers (ASTeC)

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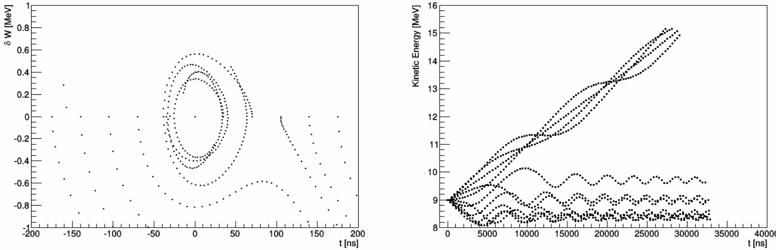


Precise FFAG simulations with 3D space charge possible

Binary Distribution

A. Gsell (PSI)

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

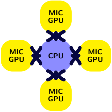
1. download from the OPAL webpage
2. choose an installation directory `$DIR` and change to this directory
3. unpack with `tar xvf OPAL-VERSION-XXX.tar.bz2`
4. setup your environment `source $DIR/OPAL-VERSION/etc/profile.d/opal.sh`

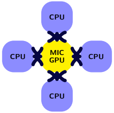
GPU Support I

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

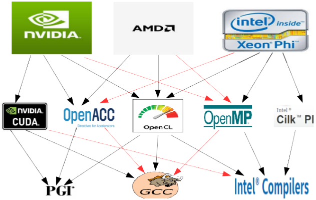
Dynamic Kernel Scheduler (DKS) [AA, U. Locans, A. Suter (2016)] is a slim software layer between host application and hardware accelerator

Heterogeneous hardware





Heterogeneous software

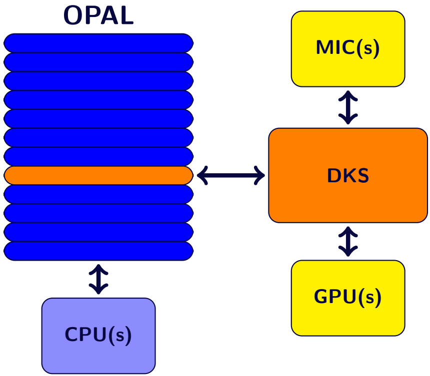


GPU Support II

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

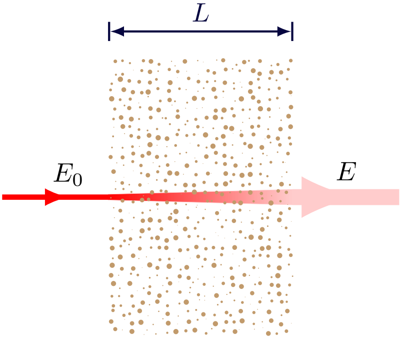
DKS concept

- **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

Particles	DKS	Degrader time (s)	Degrader speedup	Integration time (s)	Integration speedup
10^5	no	20.30		3.46	
	MIC	**2.29**	**×8**	**0.89**	**×4**
	K20	**0.28**	**×72**	**0.15**	**×23**
	K40	**0.19**	**×107**	**0.14**	**×24**
10^6	no	206.77		34.93	
	MIC	**5.38**	**×38**	**4.62**	**×7.5**
	K20	**1.41**	**×146**	**1.83**	**×19**
	K40	**1.18**	**×175**	**1.21**	**×29**
10^7	no	2048.25		351.64	
	K20	**14.4**	**×142**	**17.21**	**×20**
	K40	**12.79**	**×160**	**11.43**	**×30**

Matched Distribution with Linear Space Charge

Ch. Baumgarten, M. Frey & AA (PSI)

- **Goal:** Find a stationary distribution σ, i.e.

$$\sigma(s+L) = M\sigma(s)M^T$$

$$\sigma = \sigma(s+L) \stackrel{!}{=} \sigma(s)$$

  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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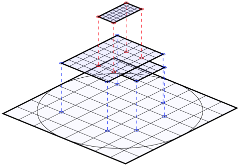
   - Adaptive Mesh Refinement (AMR) Solver
   - OPAL-T-**3d**
   - Multiobjective Optimiser

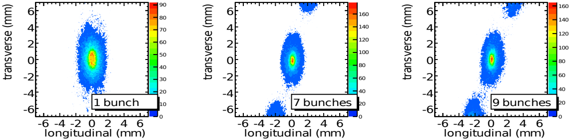
Adaptive Mesh Refinement (AMR) Solver

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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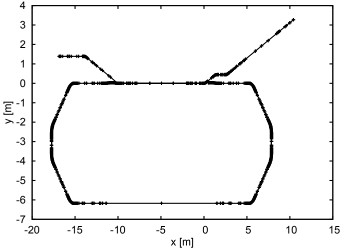
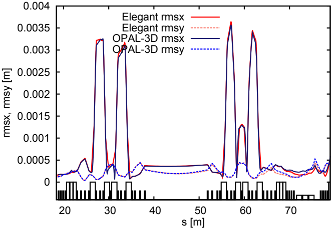
OPAL-T-3d I

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

For ERL bERLinPro

- include all elements only once although traversed twice (n×)
- add apertures to all elements
- add origin and initial orientation of beamline (elements)
- **IPAC 16 paper :** `WEPOY034 Latest Improvements of OPAL`



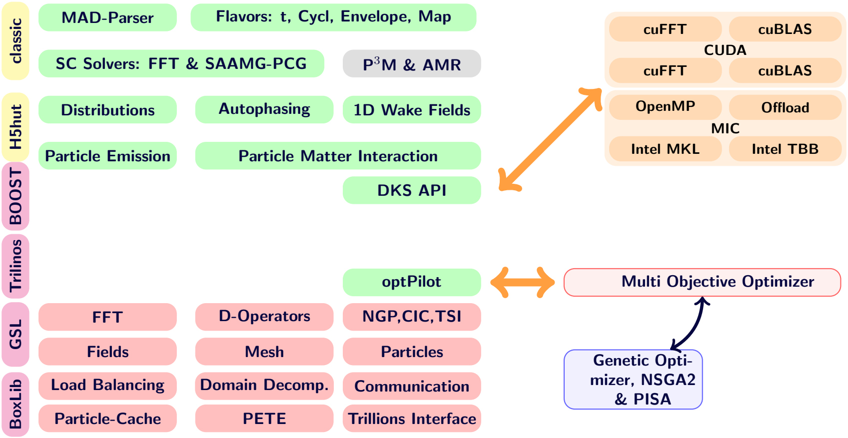


Curtesy of Ch. Metzger (HZB)

Multiobjective Optimiser

[Y. Ineichen, AA, et al. (2012), Y. Ineichen, AA, et al. (2014)]

Dynamic Kernel Scheduler



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