Cornell University
Laboratory for Elementary-Particle Physics

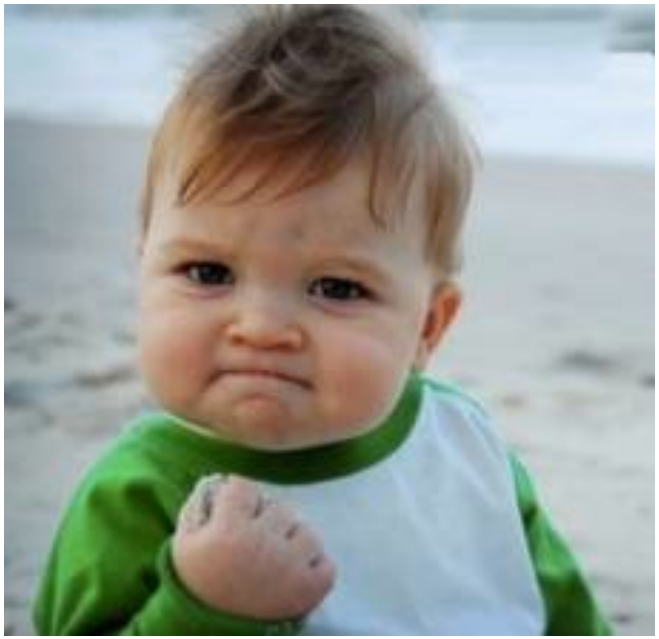
Introduction to Bmad and Tao

David Sagan & Chris Mayes
Cornell Laboratory for
Accelerator-Based Sciences and Education

In the Beginning…

Brief History of Bmad:

- Bmad is a software toolkit for the simulation of charged particles and X-rays.
- Born at Cornell in mid 1990's
- Started life as modest project: Just wanted to calculate Twiss functions and closed orbits.
- Initially Bmad used a subset of the MAD lattice syntax. Hence the name: "Baby MAD" or "Bmad" for short.



Over the years Bmad had evolved…

And Baby Grows Up...

Currently:

- ~100,000 lines of code
- ~1,000 routines

And it can do much more:

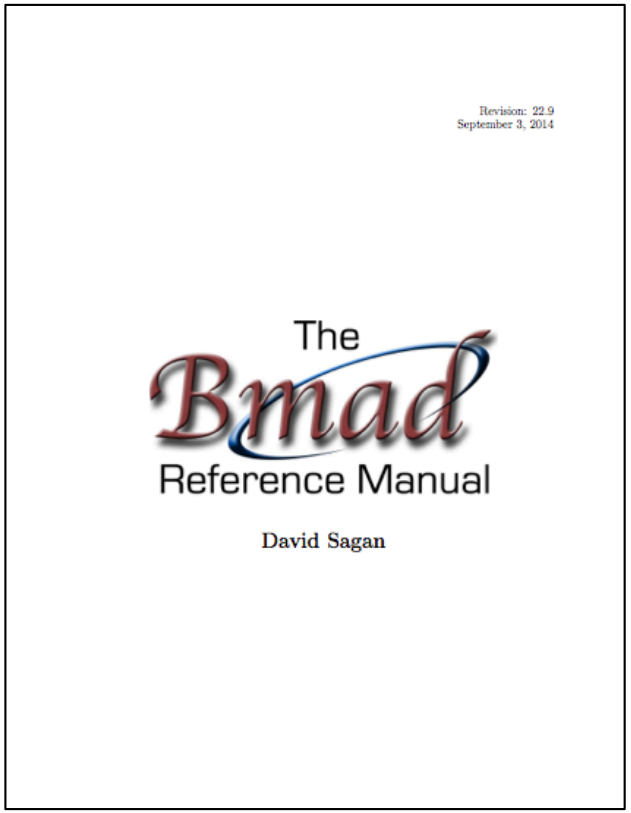
- Lattice design
- X-ray simulations
- Spin tracking
- Wakefields and HOMs
- Beam breakup simulations in ERLs
- Intra-beam scattering (IBS) simulations
- Coherent Synchrotron Radiation (CSR)
- Touschek Simulations
- Frequency map analysis
- Dark current tracking
- Etc., etc.

Overview

- Written in Fortran 2008.
- Object oriented from the ground up.

```
type (lat_struct) lat
call bmad_parser ('lat.bmad', lat)
```

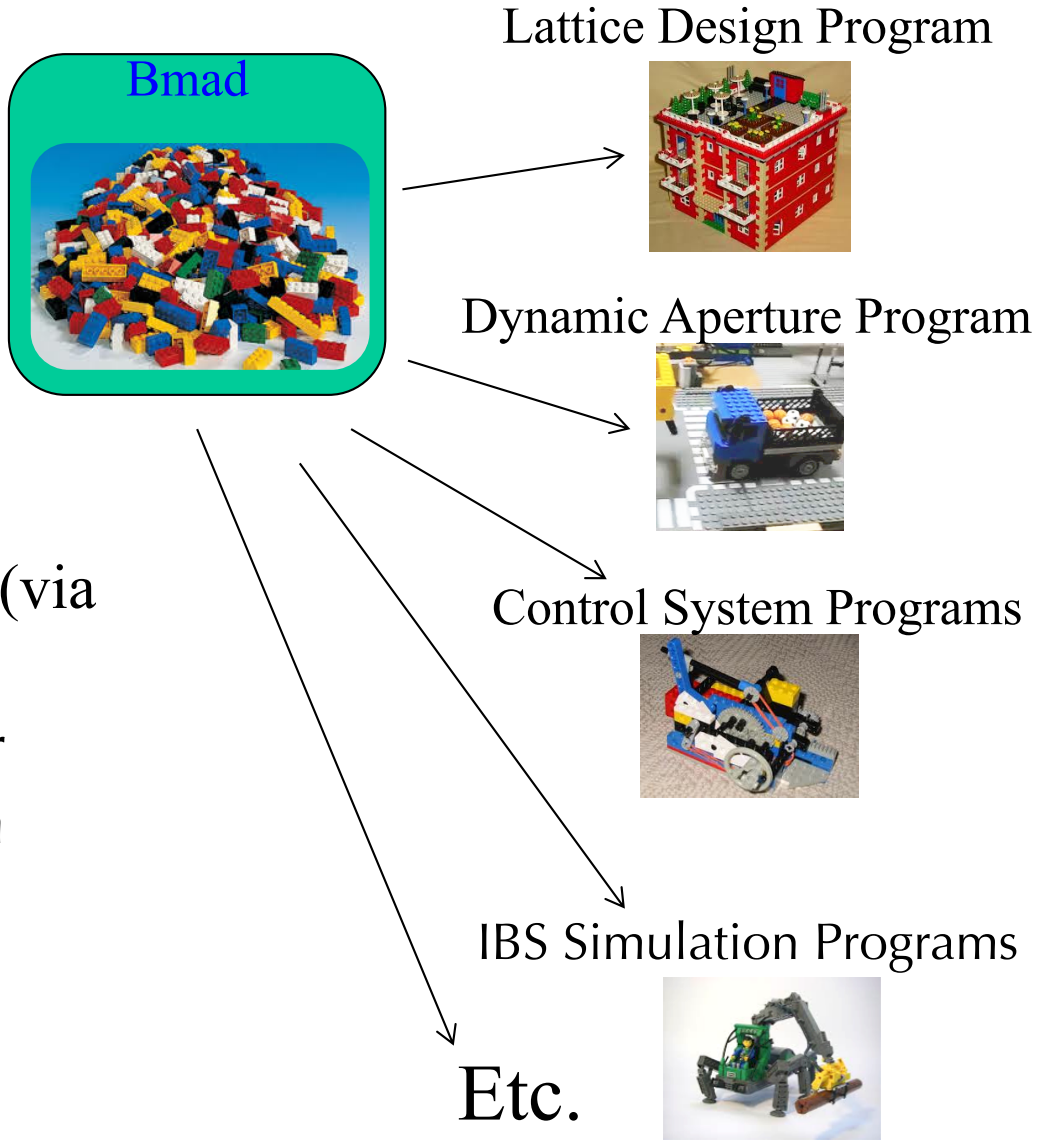
- Has structure translation code for interfacing with C++.
- With certain restrictions, Bmad can be run multi-threaded.
- Lattice files use a MAD like syntax.
- Well documented (Manual is ~500 pages).
- Open Source:
  http://www.lepp.cornell.edu/~dcs/bmad/



Bmad Philosophy

Advantages of a toolkit:

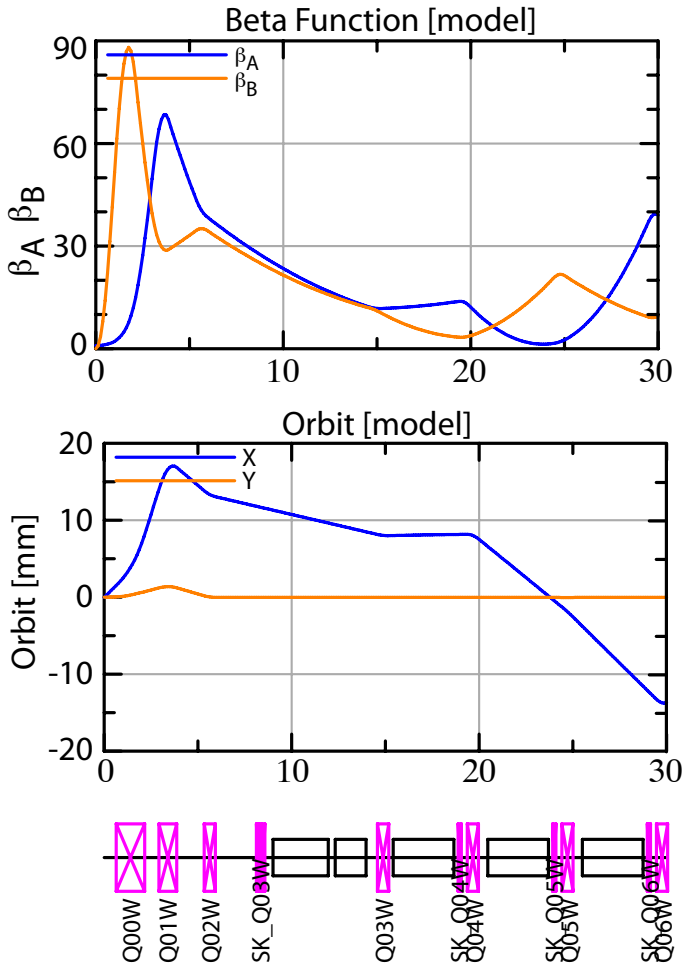
- Cuts down on the time needed to develop programs.
- Cuts down on programming errors (via code reuse).
- Provides a simple mechanism for lattice function calculations from within control system programs.
- Standardizes sharing of lattice information between programs.



Bmad Ecosystem

Due to its flexibility, Bmad has been used in a number of programs including:

- **tao** General purpose design and simulation.
- **synrad3d** 3D tracking of synch photons, including reflections, within the beam chamber.
- **cesrv** On-line data taking, simulation, and machine correction for CESR.
- **dark_current_tracker** Dark current electron simulation.
- **freq_map** Frequency map analysis.
- **ibs_sim** Analytic intra-beam scattering (IBS) calculation.
- **touschek_track** Tracking of Touschek particles.
- etc...



Code reuse: Modules developed for one program can, via Bmad, be used in other programs.

Summary of Bmad advantages

- State-of-the-art tracking methods, fast and slow
- Arbitrary trajectory 1-D CSR model with shielding
- Medium-High energy space charge model
- Field maps for any element, can overlap other elements
- Superposition: Greatly simplifies lattice layout, bookkeeping
- Patch element: Enables arbitrary arrangement of magnets
- Controller elements: define arbitrary knobs
- Continuous beam chamber walls, masks
- Forking: Multiple connected lines
- Reads MAD, XSIF, SAD lattice formats
- Translation routines to Astra, OPAL, MAD, XSIF, SAD, …
- Spin tracking
- X-ray tracking
- Dark current tracking
- Software toolkit: Maximum flexibility for custom programs

Tao: Tool for Accelerator Optics

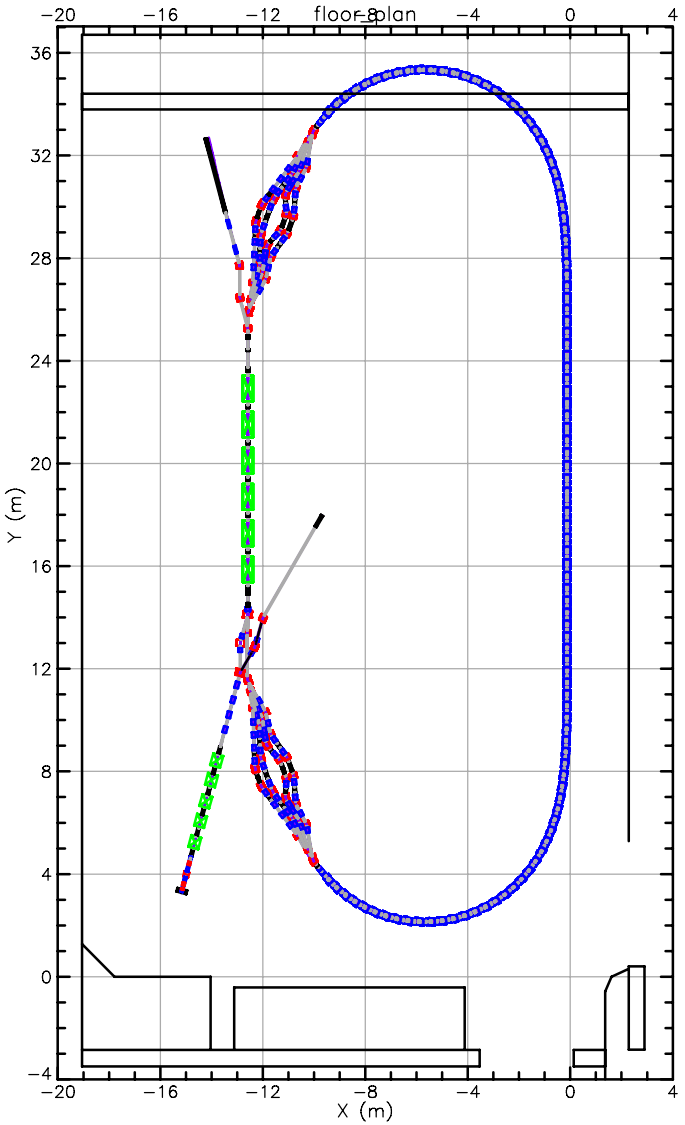
Problem: Bmad is not a program so it cannot be used "out of the box." for simple calculations.

Solution: Develop Tao - a general purpose simulation & design program with

- Twiss and orbit calculations.
- Nonlinear optimization.
- Analysis of complicated geometries.
- Etc.

Additionally: Tao's object oriented coding makes it relatively easy to extend it.

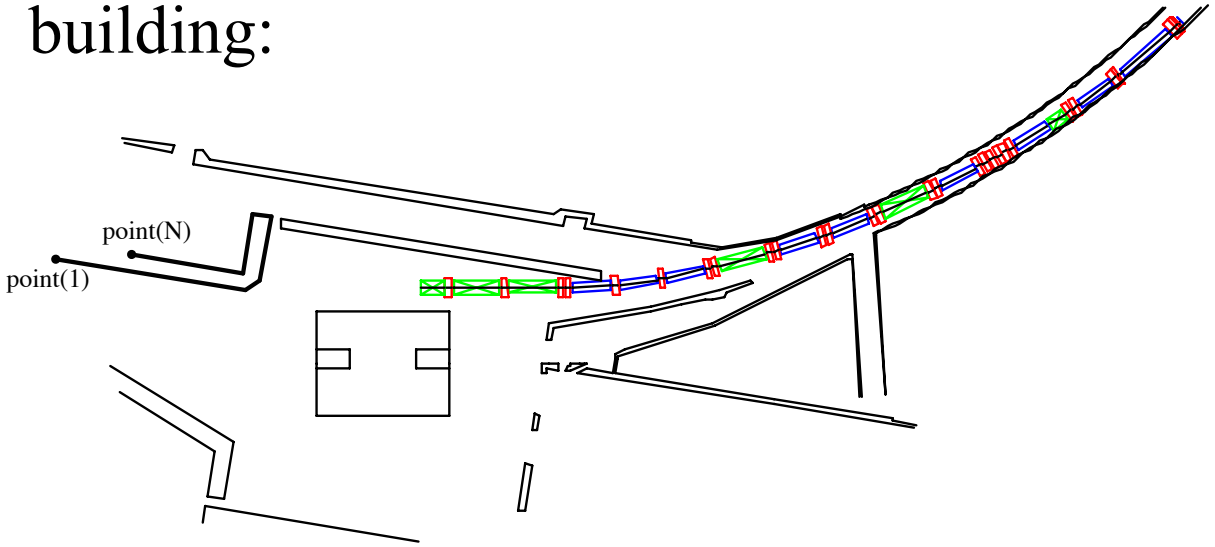
- For example: Can add custom commands to interface Tao with a control system.

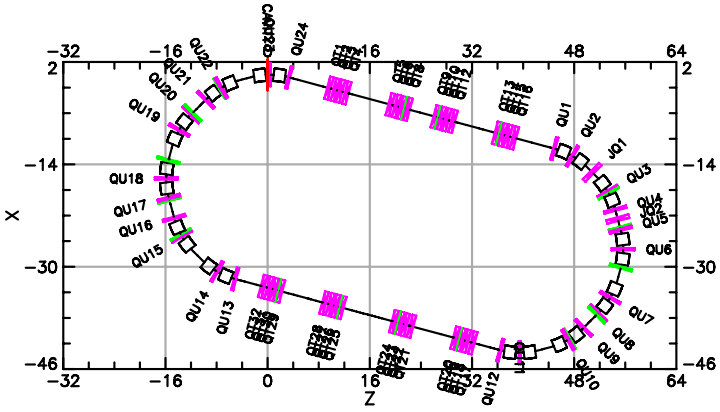


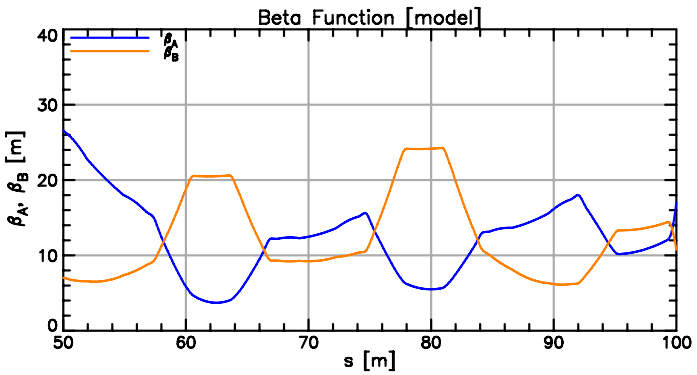
Cornell/BNL 4-pass ERL

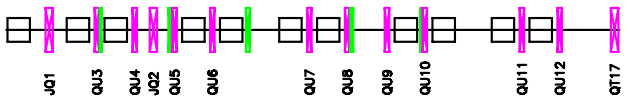
Tao generalized design

Example: Designing or modifying a machine to be/stay within an existing building:



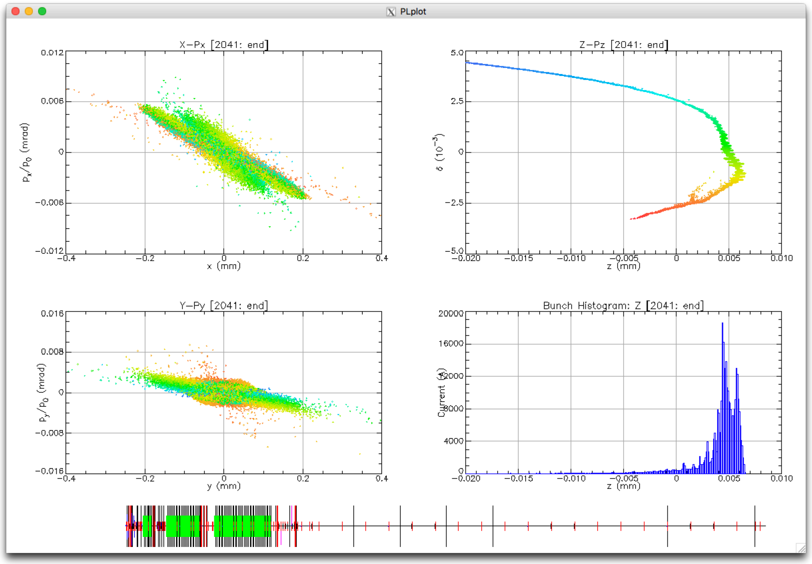


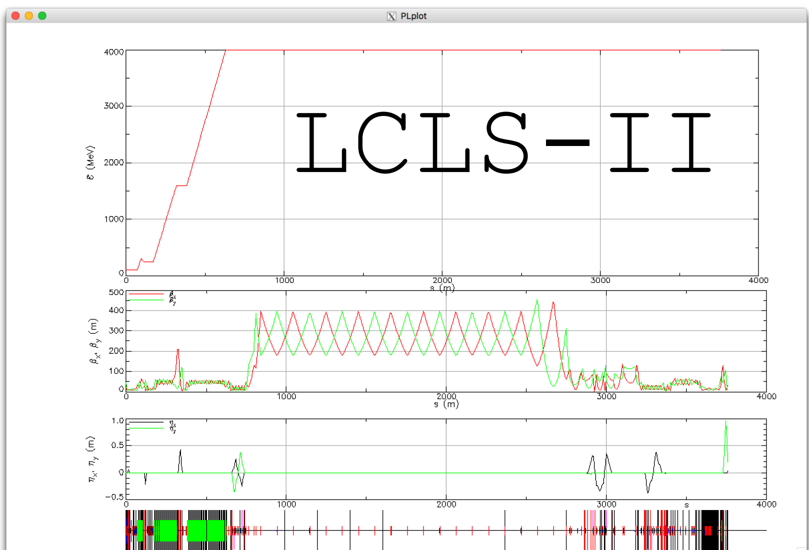




Tao with Bmad gives the flexibility of a library with the convenience of a program.

Tao command line and plot window






```
model — tao — 117×64

Tao> sho ele 1619
 Element #             1619
 Element Name: CAVL358
 Element Type: "cryo"
 Key: Lcavity
 S_start, S:  631.705741,  632.743485
 Ref_time:  2.110609E-06

 Attribute values [Only non-zero/non-default values shown]:
    1   L                            =  1.0377431E+00 m
    3   RF_FREQUENCY                 =  1.3000000E+09 Hz          RF_WAVELENGTH   =  0.230609581 m
    6   GRADIENT                     =  1.4677427E+07 eV/m
    9   VOLTAGE                      =  1.5231399E+07 Volt
   10   FRINGE_TYPE                  =  Full (4)
   13   SPIN_FRINGE_ON               =  T (1)
   18   AUTOSCALE_AMPLITUDE          =  T (1)
   19   AUTOSCALE_PHASE              =  T (1)
   24   PHI0                         =  2.7777778E-02 rad/2Pi
   31   L_HARD_EDGE                  =  1.1530479E-01 m
   32   FIELD_AUTOSCALE              =  1.0000000E+00
   33   N_CELL                       = 1
   50   DELTA_REF_TIME               =  3.4615385E-09 sec
   51   P0C_START                    =  3.9850000E+09 eV          BETA_START      =  0.999999992
   52   E_TOT_START                  =  3.9850000E+09 eV          DELTA_E         =  1.5000000E+07 eV
   53   P0C                          =  4.0000000E+09 eV          BETA            =  0.999999992
   54   E_TOT                        =  4.0000000E+09 eV          GAMMA           =  7.8278048E+03
   66   NUM_STEPS                    = 104
   67   DS_STEP                      =  1.0000000E-02 m
   76   X1_LIMIT                     =  3.5000000E-02 m
   77   X2_LIMIT                     =  3.5000000E-02 m
   78   Y1_LIMIT                     =  3.5000000E-02 m
   79   Y2_LIMIT                     =  3.5000000E-02 m

        TRACKING_METHOD               =  Bmad_Standard
        MAT6_CALC_METHOD              =  Bmad_Standard
        SPIN_TRACKING_METHOD          =  Tracking
        PTC_INTEGRATION_TYPE          =  Matrix_Kick
        FIELD_CALC                    =  Bmad_Standard
        APERTURE_AT                   =  Exit_End
        OFFSET_MOVES_APERTURE         =  F
        SYMPLECTIFY                   =  F
        FIELD_MASTER                  =  F
        CSR_CALC_ON                   =  T

Slave_status: Free
Lord_status:  Not_a_Lord

Twiss at end of element:
                     A              B                Cbar                       C_mat
  Beta (m)       32.55240066    28.24702055  |  -0.00000000   0.00000000    -0.00000000   0.00000000
  Alpha          -0.72250693     1.01776549  |  -0.00000000  -0.00000000    -0.00000000  -0.00000000
  Gamma (1/m)     0.04675588     0.07207297  |   Gamma_c =   1.00000000     Mode_Flip = F
  Phi (rad)      29.60127042    36.86380039              X             Y              Z
  Eta (m)        -0.00000000    -0.00000000    -0.00000000   -0.00000000    -1.53091755
  Etap           -0.00000000     0.00000000    -0.00000000    0.00000000    -0.00000000

Orbit:  Electron   State: Alive
         Position[mm] Momentum[mrad]        Spin    |
  X:     -0.00000000  -0.00000000                   | Particle [sec]:      2.11060937E-06  E_tot;  4.0000E+09
  Y:      0.00000000  -0.00000000                   | Part-Ref [sec]:     -4.23516474E-22  PC:     4.0000E+09
  Z:      0.00000000   0.00000000                   | (Ref-Part)*Vel [m]:  1.26967044E-13  Beta:    1.000000

Tao> |
```

Summary of Tao advantages

- Design tool
- Fast online optics calculation
- Multiple optimization methods
- Bunch tracking with CSR, Space charge
- Response of anything to anything: effect of quad misalignments, etc.
- Wave analysis: discover isolated orbit and focusing errors.
- Built-in plotting
- Customizable via hook routines, e.g. interface with a control system
- Python interface for automation, advanced GUIs, also interface with control systems