LCLS Virtual Accelerator:
Online Model

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U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

LCLS Virtual Accelerator

We would like to build:

- Detailed computer model and simulation framework of the machine
- Fully start-to-end, from laser shape on the cathode to X-ray production to X-ray tracking to the sample
- Seamless or simple translation from code to code without the need of an expert
- Utilizes HPC resources without the need of a parallel computing expert

This would enable:

- High-fidelity, comprehensive beam physics simulations
- Virtual beam experiments
- Discovery of optimal, robust machine settings

LCLS Online Model

- Subset of the virtual accelerator
- Fast
- Update continuously as the machine is running
- Adjusts automatically to reflect known measurements (wire-scan, BPM data)
- High-level `knobs' for rapid tuning
- Scriptable
- Reliable save/load machine state

Plan

Choose a backbone simulation framework that:

- Captures the most physics effects
- Well-supported and documented by the developers
- Mature
- Produces inputs to other programs
- Customizable

Physics features of various accelerator codes

SLAC

Physics features	MAD8	Elegant	Bmad/Tao	SLAC-Matlab	Impact	OPAL	Astra	GPT	Ocelot
design tool	X	X	X						
Linear optics	X	X	X	X		X			X
Nonlinear optics	X	X	X						
Taylor maps, symplectic tracking, analysis			X						
Wakefields		X	X		X	X			X
low energy space charge					X	X	X	X	X
high energy space charge			X		X	X	X	X	X
Inchoherent synchrotron radiation		X	x		X	X			
coherent synchrotron radiation (CSR)		X	X		X	X		X	X
CSR with shielding			X						
Field map tracking		partial	X		X	X	X	X	
x-ray tracking			X						
spin tracking			X		?				
Touschek scattering		X	X						
intrabeam scattering		X	X		X				
Cavity higher-order modes (HOMs)			X						
Dark current tracking			X			X	X	X	

Practical features of various accelerator codes

Code features	MAD8	Elegant	Bmad/Tao	SLAC-Matlab	Impact	OPAL	Astra	GPT	Ocelot
SLAC specific developer support		partial	X	X	X	partial			
Active development		X	X	X	X	X			X
Documented	X	X	X			X	X	X	
customizable as a software library			X	X				X	
open source	X	X	X	X		X			X
Used as online model at other laboratories		X	X	X					X
Parallel		X	partial		X	X		$$$	
GPU support		X							
Free	X	X	X	X	X	X	X		X
MAD-like lattice syntax	X	X	X	X		X			
Lattice control structures			X	somewhat					
Birthdate		1988	1996					2002	2014
User base (small, medium, large)	L	L	M	S	S	M	L	M	S

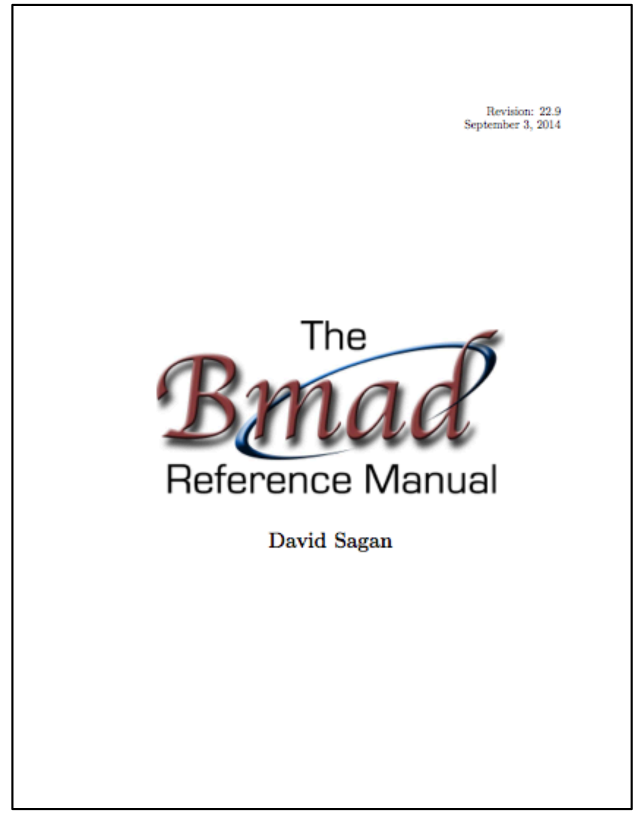
Bmad Overview

SLAC

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

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

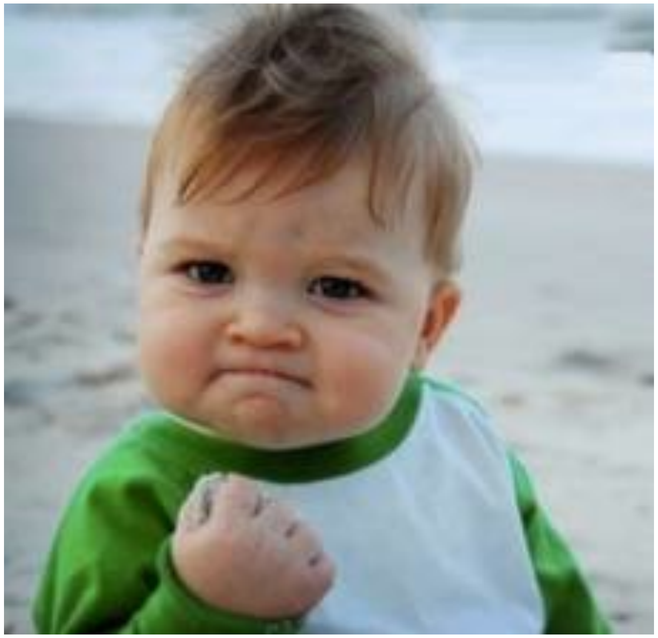
- Has structure translation code for interfacing with C++.
- With certain restrictions, Bmad can be run multi-threaded.
- Lattice files use a MAD like syntax.
- Well documented (Manual is ~500 pages).
- Open Source:
  http://www.lepp.cornell.edu/~dcs/bmad/



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 1990s
- 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.

Bmad Philosophy

Advantages of a toolkit:

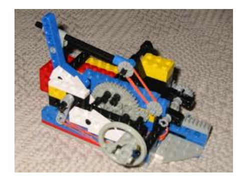
- Cuts down on the time needed to develop programs.
- Cuts down on programming errors (via code reuse).
- Provides a simple mechanism for lattice function calculations from within control system programs.
- Standardizes sharing of lattice information between programs.

Bmad

Lattice Design Program

Dynamic Aperture Program

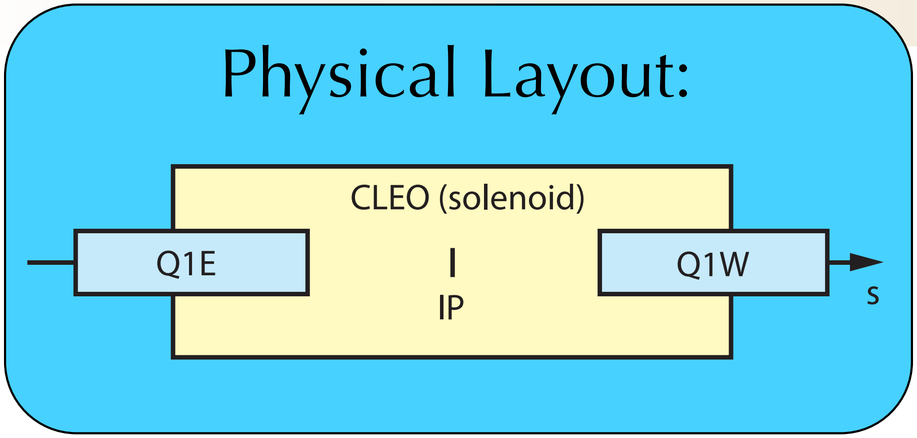
Control System Programs

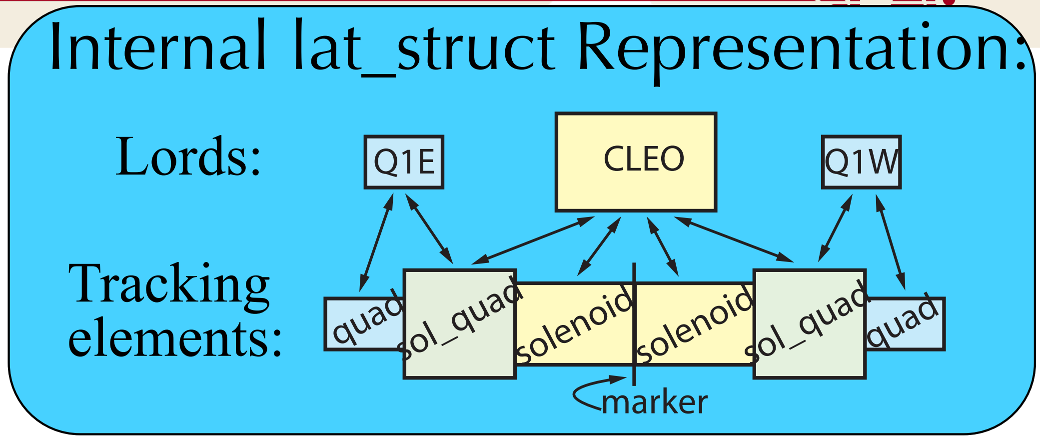


IBS Simulation Programs

Etc.

Superposition





Superposition allows element overlap. In the lattice file:

```
cesr: line = (... q1e, dft, ip, dft, q1w ...)
cleo: solenoid, l = 3.5, superimpose, ref = ip
```

And Bmad does the bookkeeping…

Simplifies life for both user and programmer:

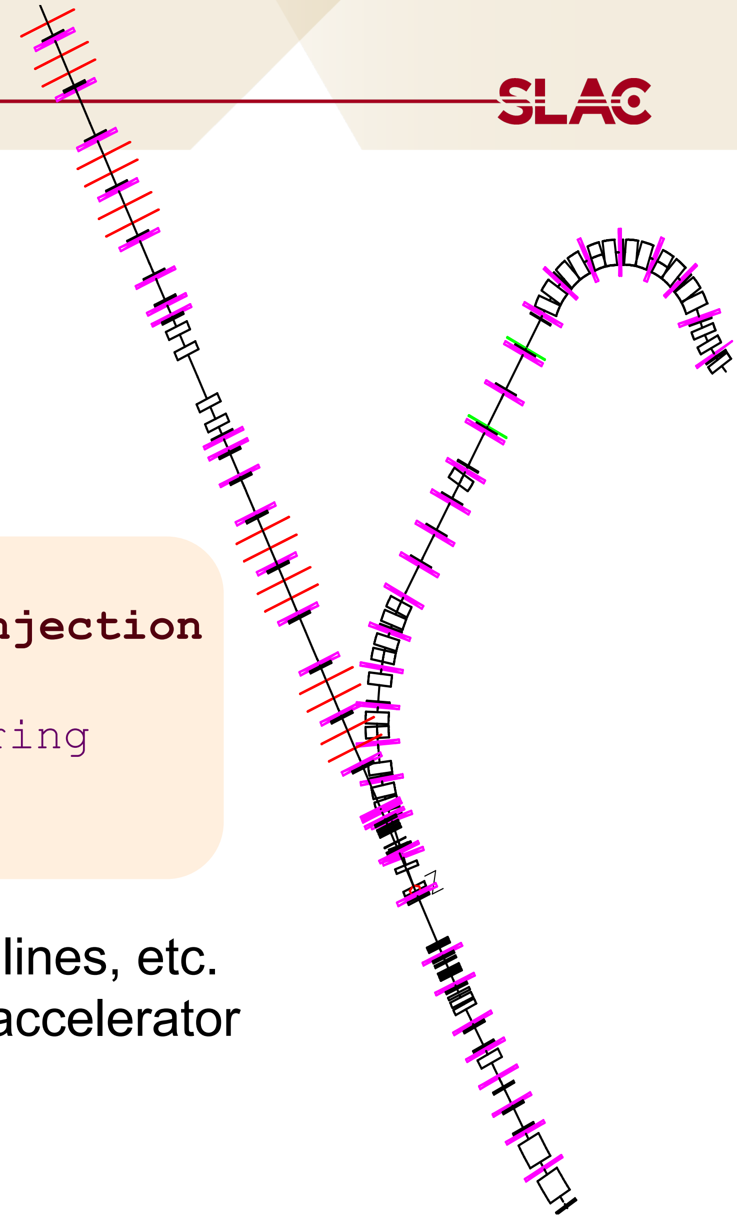
- Simplifies lattice file construction
- Simplifies varying element attributes in a program

Forking

- Bmad can join different beam lines using fork elements.
- Example: SuperKEKB Low Energy Ring (LER) injection

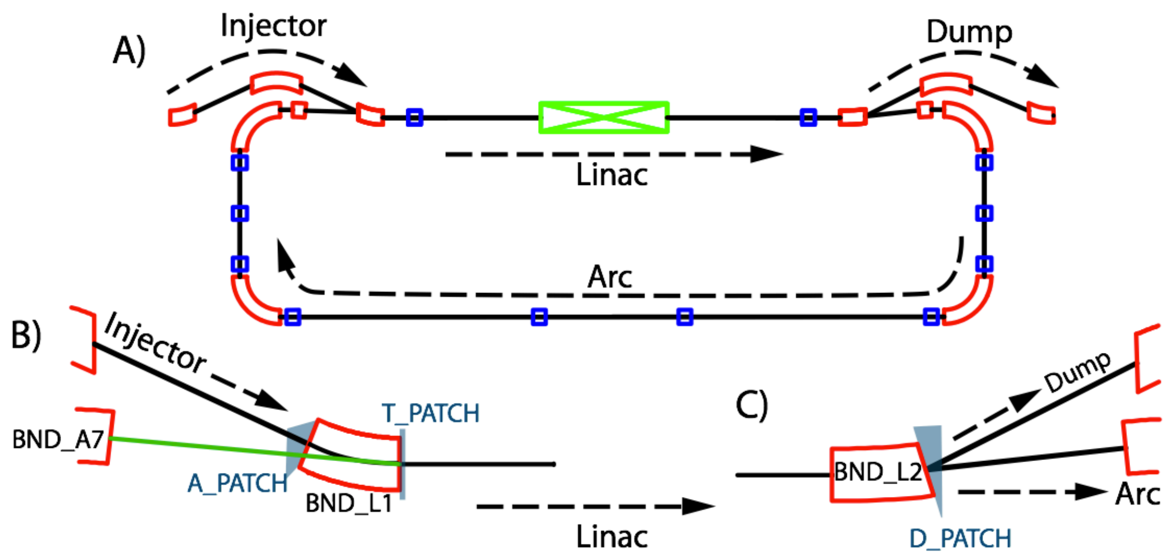
```
to_LER: fork, to_line = ler, to_element = injection
inj: line = (..., to_LER)   ! injection line
LER: line = (..., injection, ...)    ! LER ring
use, inj
```

- Can splice together rings, dump lines, Linacs, X-ray lines, etc.
➔ One lattice can hold the description of the entire accelerator complex.



Multipass

Lines having common elements. Example ERL loop:




```
BEND_L1: sbend, angle = -25*pi/180, l = 0.2, ...
BEND_L2: BEND_L1
A_PATCH: patch, flexible = T
D_PATCH: patch, x_offset = -0.034, x_offset = asin(-0.32)
INJECT: line = (...)
LINAC: line[multipass] = (BEND_L1, ..., BEND_L2)
ARC: line = (..., BEND_A7)
DUMP: line = (...)
ERL: line = (INJECT, LINAC, ARC, A_PATCH, LINAC, D_PATCH, DUMP)
```

Tracking method selection

Can set how each element is tracked:

• `bmad_standard`	Fast, nonsymplectic
• `symp_lie_ptc`	Symplectic tracking using PTC
• `taylor`	Taylor map tracking using PTC
• `linear`	Linear tracking
• `runge_kutta`	Track through fields.
• `custom`	Tracking with custom code
• …	

```
my_ele: em_field, tracking_method = runge_kutta, field_calc=custom, ...
```

Advantages:

- Enables simulation of unique element types
- Can compare different tracking methods

All elements and tracking methods

Element Class	Bmad_Standard	Boris	Custom	Linear	MAD	Runge_Kutta	Symp_Lie_Bmad	Symp_Lie_PTC	Symp_Map	Taylor	Time_Runge_Kutta
ab_multipole	D		X	X				X	X	X	
beambeam	D		X	X							
bend_sol_quad			X				D				
capillary	D		X								
crystal	D		X								
custom		X	D	X		X					X
drift	D	X	X	X	X	X		X	X	X	X
e_gun			X								D
ecollimator	D	X	X	X		X		X	X	X	X
elseparator	D	X	X	X	X	X		X	X	X	X
em_field		X	X			D					X
floor_shift	D		X								
hkicker	D	X	X	X		X		X	X	X	X
instrument	D	X	X	X		X		X	X	X	X
kicker	D	X	X	X		X		X	X	X	X
lcavity	D	X	X	X		X		X	X	X	X
marker	D		X	X				X	X	X	
match	D		X							*	
monitor	D	X	X	X		X		X	X	X	X
mirror	D		X								
multipole	D		X	X				X	X	X	
multilayer	D		X								
octupole	D	X	X	X		X		X	X	X	X
patch	D		X			X		X		X	
quadrupole	D	X	X	X	X	X	X	X	X	X	X
rbend	D		X	X	X			X	X	X	
rcollimator	D	X	X	X		X		X	X	X	X
rfcavity	D	X	X	X	X	X		X	X	X	X
sad_mult	D		X	X				X	X	X	
sample	D		X								
sbend	D		X	X	X	X		X	X	X	X
sextupole	D	X	X	X	X	X		X	X	X	X
solenoid	D	X	X	X	X	X	X	X	X	X	X
sol_quad	D	X	X	X		X	X	X	X	X	X
taylor	X		X	X						D	
vkicker	D	X	X	X		X		X	X	X	X
wiggler (map type)		X	X	X		X	X	X	X	X	X
wiggler (periodic type)	D	X	X	X		X[a]	X[a]	X[a]	X[a]	X[a]	

[a] See §3.43.2 for more details

Table 5.1: Table of available **tracking_method** switches for a given element class. "D" denotes the default method. "X" denotes an available method. "*" denotes that the Taylor map will only be first order.

Spin

	Bmad_Standard	Custom	Symp_Lie_PTC	Tracking
ab_multipole	D	X		
beambeam		X		
bend_sol_quad	D	X	X	X
capillary				
crystal				
custom		D		X
drift	D	X	X	X
e_gun		X		D
ecollimator	D	X	X	X
elseparator	D	X	X	X
em_field		X		D
hkicker	D	X	X	X
instrument	D	X	X	X
kicker	D	X	X	X
lcavity	D	X	X	X
marker	D	X	X	X
match		X		
mirror				
monitor	D	X	X	X
multipole	D	X	X	
multilayer				
octupole	D	X	X	X
patch		X	X	
quadrupole	D	X	X	X
rbend	D	X	X	X
rcollimator	D	X	X	X
rfcavity	D	X	X	X
sad_mult		X		
sample				
sbend	D	X	X	X
sextupole	D	X	X	X
solenoid	D	X	X	X
sol_quad	D	X	X	X
taylor				
vkicker	D	X	X	X
wiggler	D	X	X	X

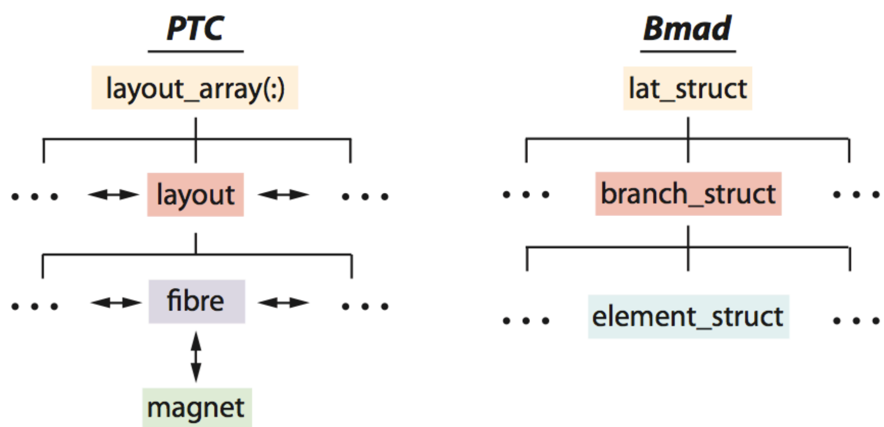
Table 5.3: Table of available **spin_tracking_method** switches for a given element class. "D" denotes the default method. "X" denotes an available method.

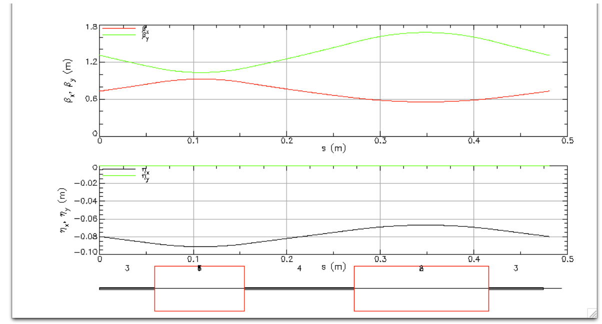
Etienne Forest’s FPP/PTC

Etienne Forest’s FPP/PTC simulation toolkit:

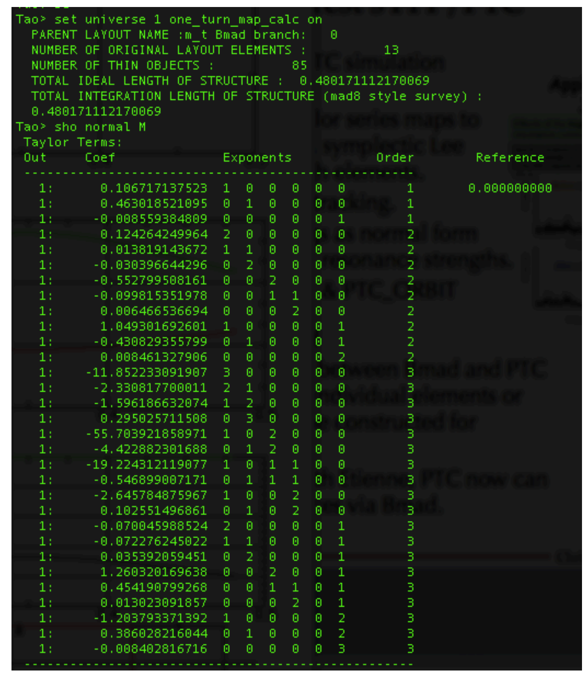
- Taylor maps to arbitrary order via symplectic integration through elements.
- Spin tracking.
- Normal form analysis.
- Amplitude Dependent Spin Tune and Invariant Spin Field calculations.
- Also used in MAD-X & PTC_ORBIT

Interface routines between Bmad and PTC allow tracking of individual elements or PTC lattices can be constructed for analysis.





FFAG cell



```
Tao> set universe 1 one_turn_map_calc on
  PARENT LAYOUT NAME :m_t Bmad branch:   0
  NUMBER OF ORIGINAL LAYOUT ELEMENTS :          13
  NUMBER OF THIN OBJECTS :           85
  TOTAL IDEAL LENGTH OF STRUCTURE :  0.480171112170069
  TOTAL INTEGRATION LENGTH OF STRUCTURE (mad8 style survey) :
  0.480171112170069
Tao> sho normal M
 Taylor Terms:
 Out     Coef                  Exponents           Order        Reference
 ----------------------------------------------------------------
   1:      0.106717137523  1  0  0  0  0  0            1       0.000000000
   1:      0.463018521095  0  1  0  0  0  0            1
   1:     -0.008559384809  0  0  0  0  0  1            1
   1:      0.124264249964  2  0  0  0  0  0            2
   1:      0.013819143672  1  1  0  0  0  0            2
   1:     -0.030396644296  0  2  0  0  0  0            2
   1:     -0.552799508161  0  0  2  0  0  0            2
   1:     -0.099815351978  0  0  1  1  0  0            2
   1:      0.006466536694  0  0  0  2  0  0            2
   1:      1.049301692601  1  0  0  0  0  1            2
   1:     -0.430829355799  0  1  0  0  0  1            2
   1:      0.008461327906  0  0  0  0  0  2            2
   1:    -11.852233091907  3  0  0  0  0  0            3
   1:     -2.330817700011  2  1  0  0  0  0            3
   1:     -1.596186632074  1  2  0  0  0  0            3
   1:      0.295025711508  0  3  0  0  0  0            3
   1:    -55.703921858971  1  0  2  0  0  0            3
   1:     -4.422882301688  0  1  2  0  0  0            3
   1:    -19.224312119077  1  0  1  1  0  0            3
   1:     -0.546899007171  0  1  1  1  0  0            3
   1:     -2.645784875967  1  0  0  2  0  0            3
   1:      0.102551496861  0  1  0  2  0  0            3
   1:     -0.070045988524  2  0  0  0  0  1            3
   1:     -0.072276245022  1  1  0  0  0  1            3
   1:      0.035392059451  0  2  0  0  0  1            3
   1:      1.260320169638  0  0  2  0  0  1            3
   1:      0.454190799268  0  0  1  1  0  1            3
   1:      0.013023091857  0  0  0  2  0  1            3
   1:     -1.203793371392  1  0  0  0  0  2            3
   1:      0.386028216044  0  1  0  0  0  2            3
   1:     -0.008402816716  0  0  0  0  0  3            3
 ----------------------------------------------------------------
```

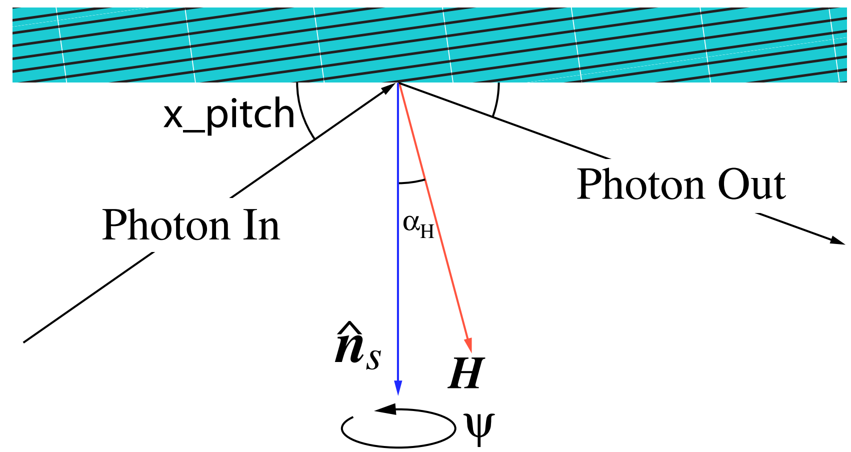
One turn map calc in Tao

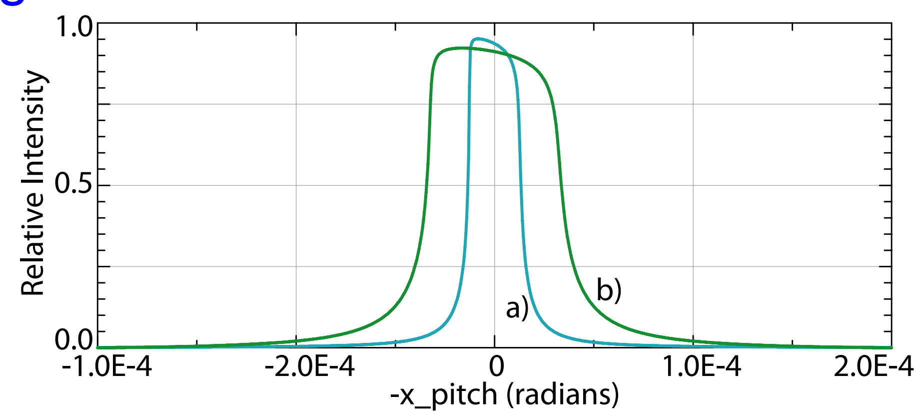
X-ray simulation

Both incoherent and coherent ray-tracing implemented (but needs more testing).

X-ray tracking elements developed:

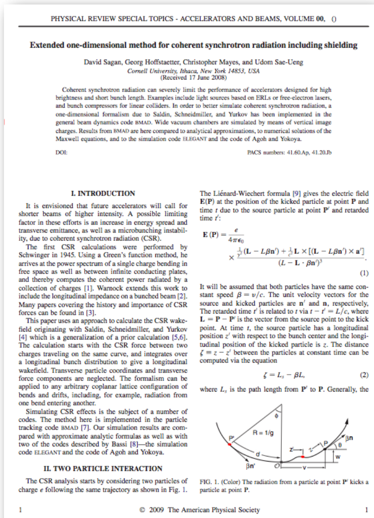
- Crystal ! Bragg & Laue diffraction
- Capillary ! Focus X-rays
- Mirror
- Multilayer Mirror
- Diffraction_plate ! Apertures, Zone plates





Bragg crystal diffraction simulation

CSR with Shielding


PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 00, ()

Extended one-dimensional method for coherent synchrotron radiation including shielding

David Sagan, Georg Hoffstaetter, Christopher Mayes, and Udom Sae-Ueng

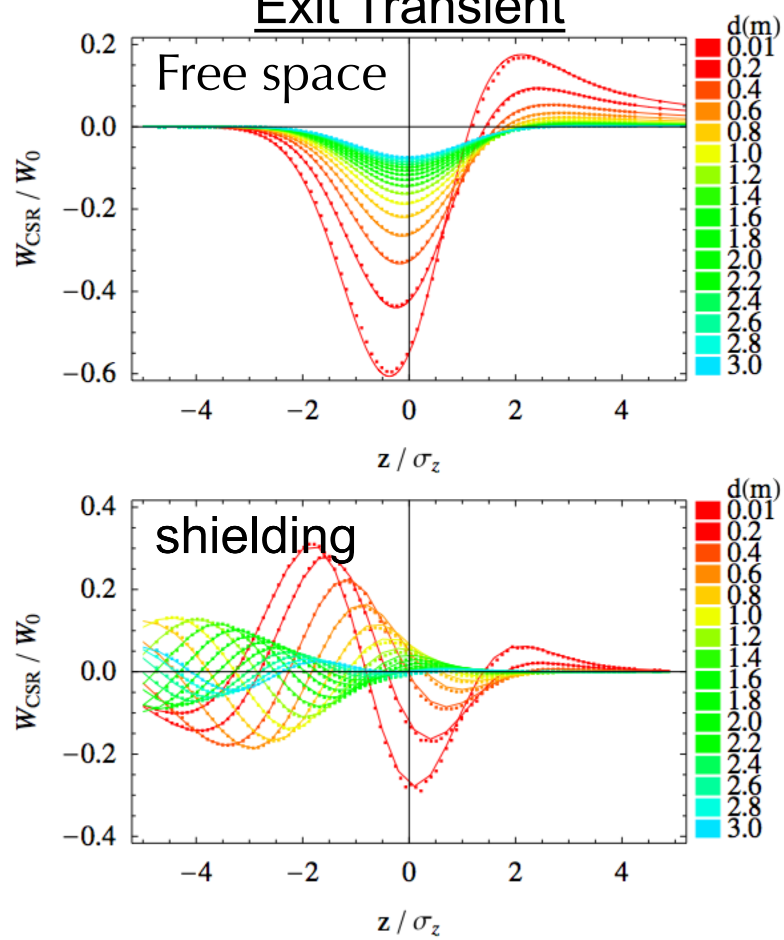
Cornell University, Ithaca, New York 14853, USA

(Received 17 June 2008)

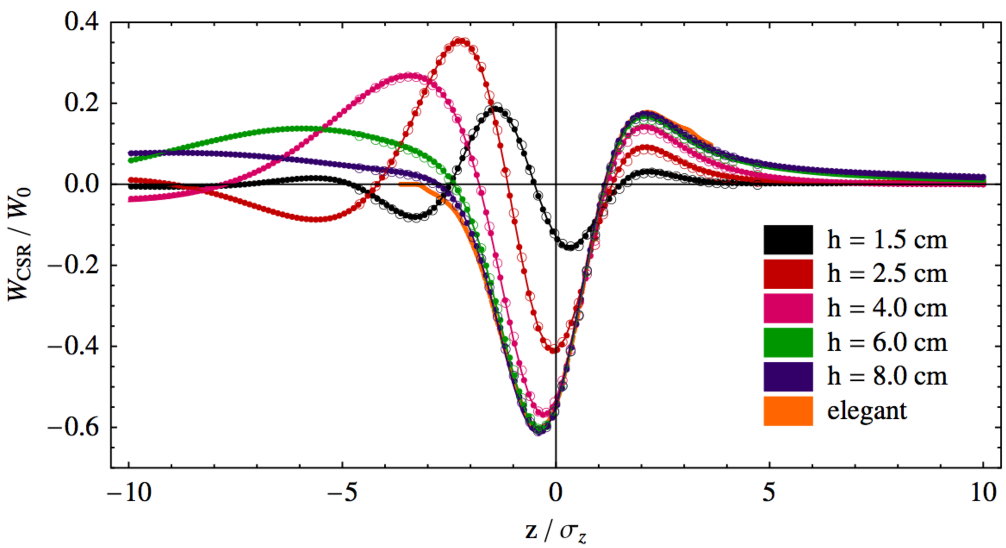
We developed and benchmarked a 1-D CSR simulation technique with shielding by the vacuum chamber in Bmad

[Sagan, Hoffstaetter, Mayes, Sae-Ueng PRST-AB **12**, 040703 (2009)]

Exit Transient



Compared with Agoh & Yokoya



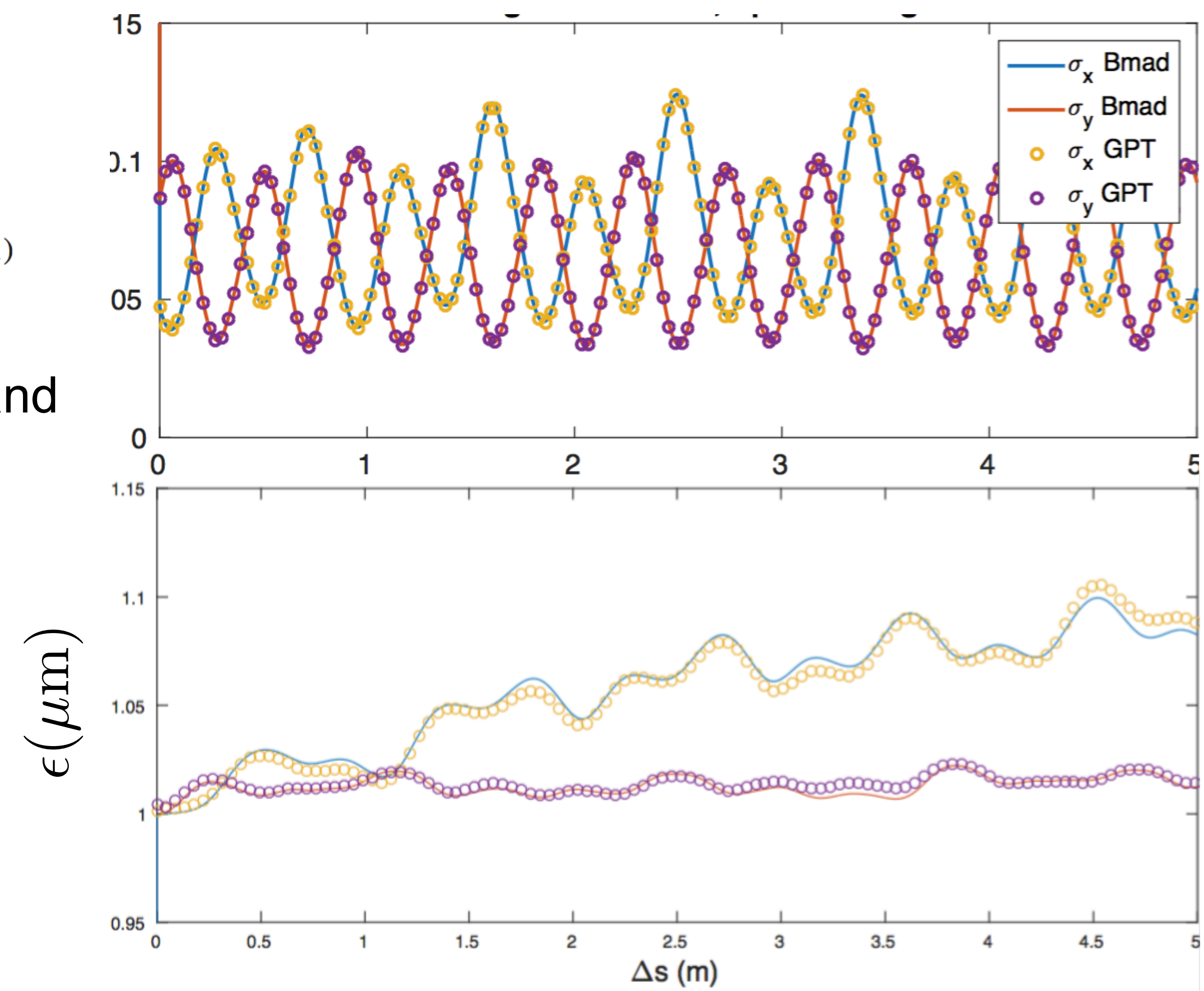
Transverse Space Charge

Also in the 2009 paper was an excellent approximation of the space charge kick due to a Gaussian slice

$$dK_{\mathrm{SC}} \approx \frac{r_c mc^2 \mathrm{sign}(\zeta)\rho(z')dz'}{\sigma_x\sigma_y \exp[\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}] + \frac{\sigma_x^2+\sigma_y^2}{\sigma_x+\sigma_y}\gamma|\zeta| + \gamma^2\zeta^2}. \quad (31)$$

This includes both longitudinal and transverse space charge

<u>1 nC bunch through straight FFAG section at 42 MeV</u>

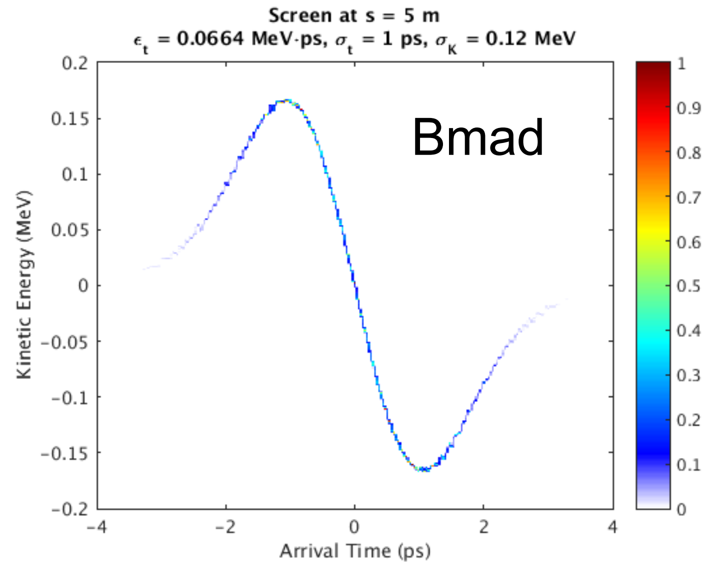


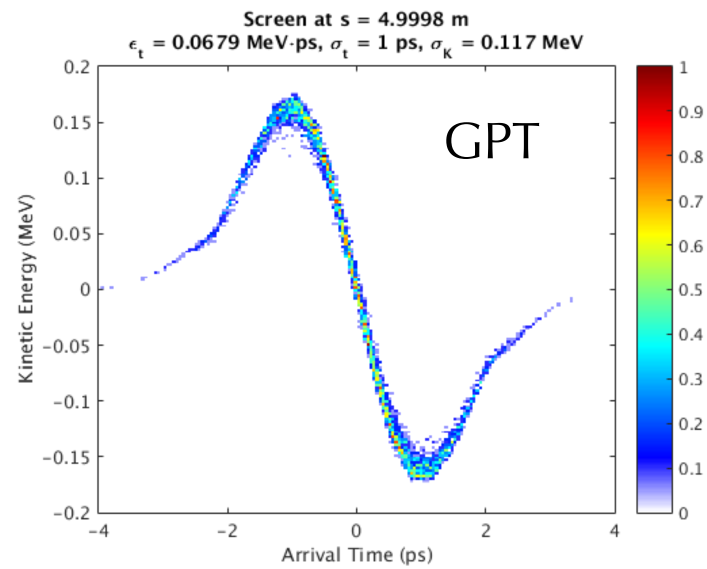
Longitudinal Space Charge

Also in the 2009 paper was an excellent approximation of the space charge kick due to a Gaussian slice

$$dK_{\rm SC} \approx \frac{r_c mc^2 \mathrm{sign}(\zeta)\rho(z')dz'}{\sigma_x\sigma_y \exp[\frac{x^2}{2\sigma_x^2}+\frac{y^2}{2\sigma_y^2}]+\frac{\sigma_x^2+\sigma_y^2}{\sigma_x+\sigma_y}\gamma|\zeta|+\gamma^2\zeta^2}. \quad (31)$$

This includes both longitudinal and transverse space charge



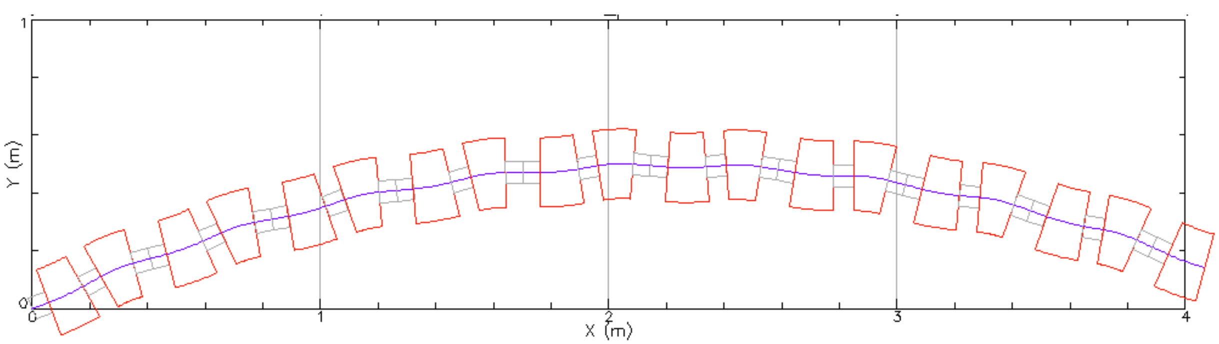


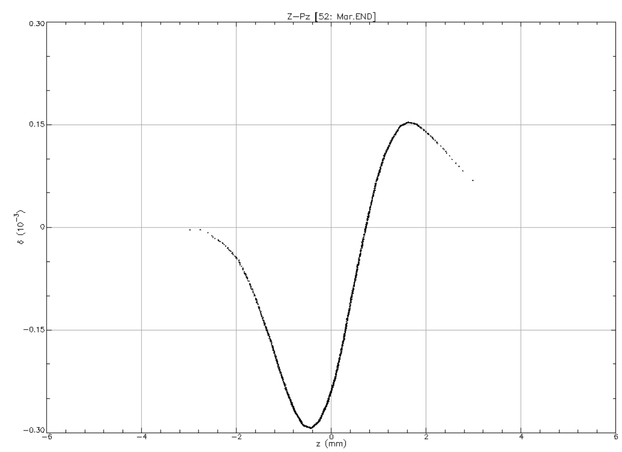
Page Headline

More general 1-D CSR model

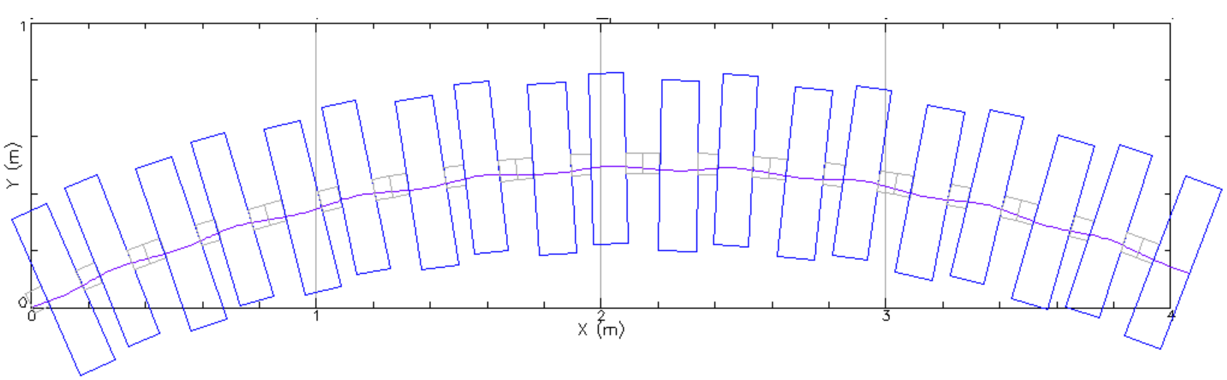
- The old code and 2009 paper assumed that the beam followed the reference coordinate system
- The new code has been generalized to deal with arbitrary orbits and is currently being benchmarked

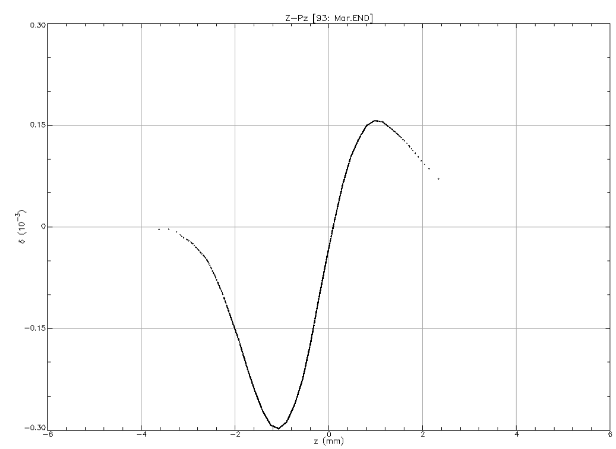
Beam follows reference (bends with quad moment)





Beam orbit with offset quads



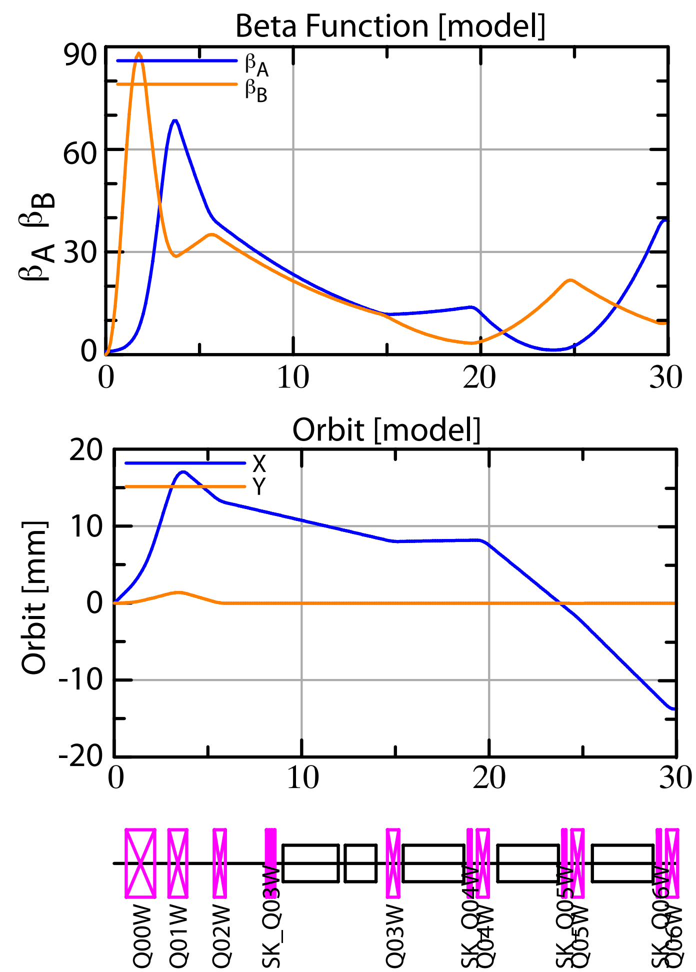


Bmad Ecosystem

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

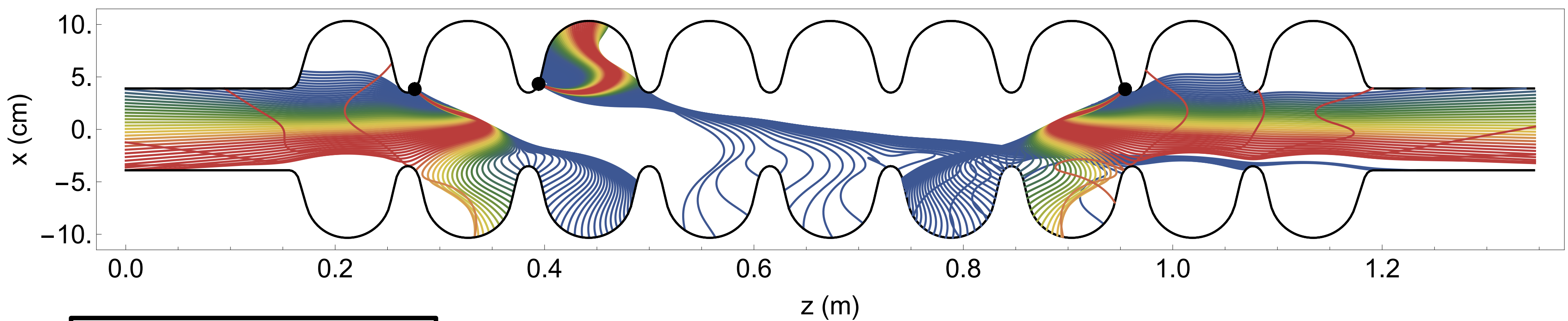
- **tao** General purpose design and simulation.
- **synrad3d** 3D tracking of synch photons, including reflections, within the beam chamber.
- **cesrv** On-line data taking, simulation, and machine correction for CESR.
- **dark_current_tracker** Dark current electron simulation.
- **freq_map** Frequency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

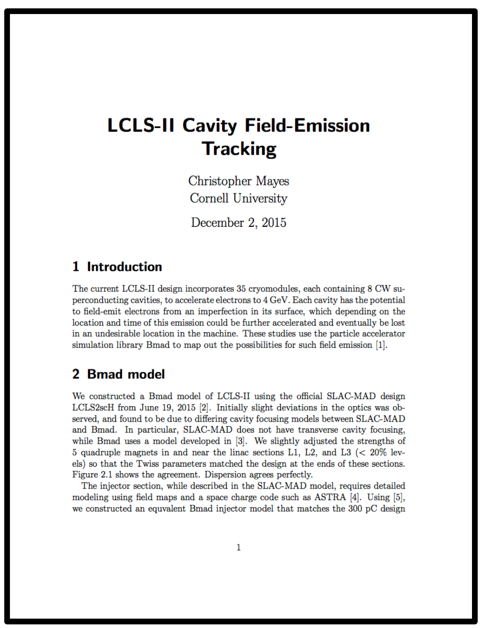
Code reuse: Modules developed for one program can, via Bmad, be used in other programs.



Dark Current Tracking for LCLS2

Field emitters





LCLS-II Cavity Field-Emission Tracking

Christopher Mayes
Cornell University

December 2, 2015

1 Introduction

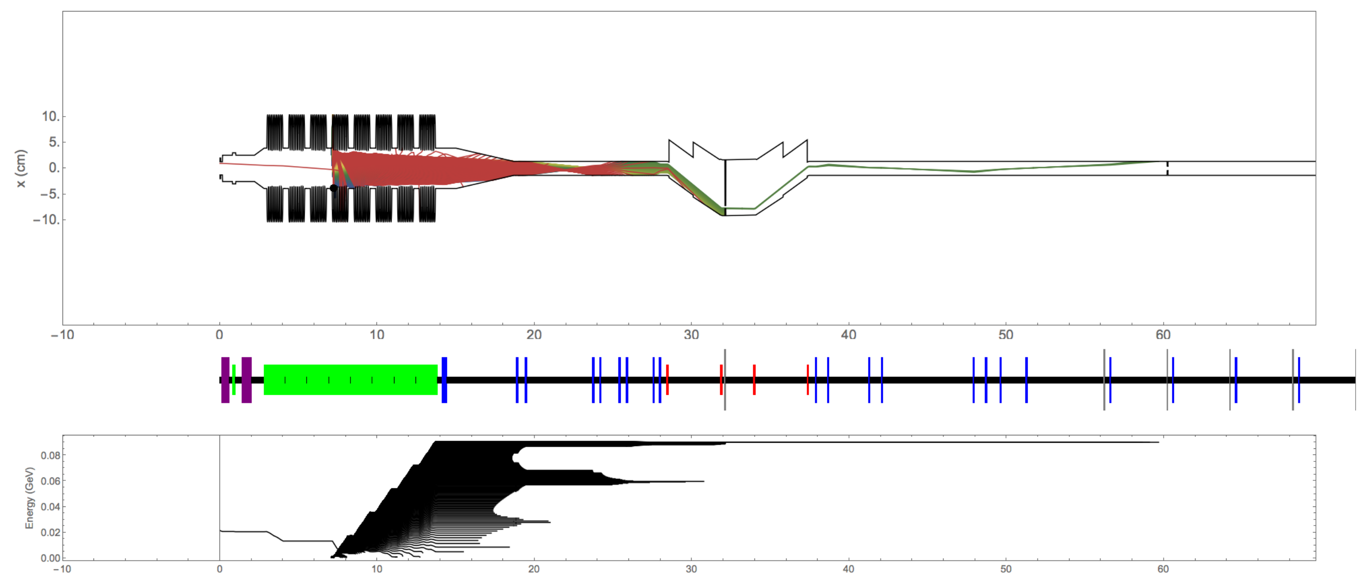
The current LCLS-II design incorporates 35 cryomodules, each containing 8 CW superconducting cavities, to accelerate electrons to 4 GeV. Each cavity has the potential to field-emit electrons from an imperfection in its surface, which depending on the location and time of this emission could be further accelerated and eventually be lost in an undesirable location in the machine. These studies use the particle accelerator simulation library Bmad to map out the possibilities for such field emission [1].

2 Bmad model

We constructed a Bmad model of LCLS-II using the official SLAC-MAD design LCLS2scH from June 19, 2015 [2]. Initially slight deviations in the optics was observed, and found to be due to differing cavity focusing models between SLAC-MAD and Bmad. In particular, SLAC-MAD does not have transverse cavity focusing, while Bmad uses a model developed in [3]. We slightly adjusted the strengths of 5 quadruple magnets in and near the linac sections L1, L2, and L3 (< 20% levels) so that the Twiss parameters matched the design at the ends of these sections. Figure 2.1 shows the agreement. Dispersion agrees perfectly.

The injector section, while described in the SLAC-MAD model, requires detailed modeling using field maps and a space charge code such as ASTRA [4]. Using [5], we constructed an equvalent Bmad injector model that matches the 300 pC design

1



https://www.classe.cornell.edu/~cem52/LCLS2/2015_09_16-LCLS2_dark_current.pdf

Tao: Tool for Accelerator Optics

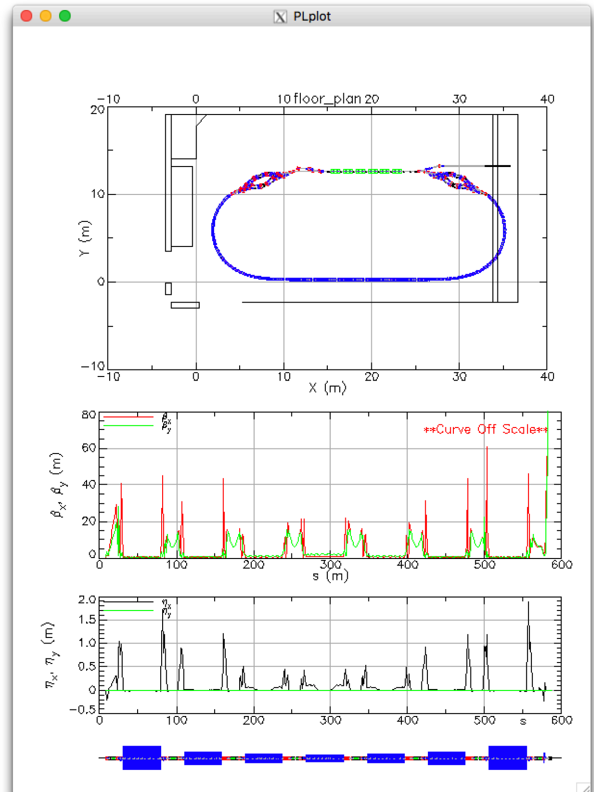
Problem: Bmad is not a program so it cannot be used “out of the box” for simple calculations.

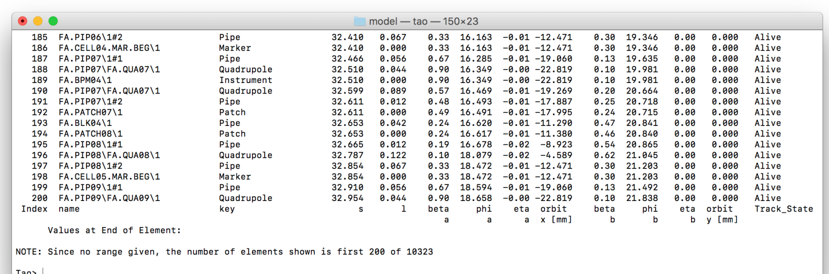
Solution: Develop Tao - a general purpose simulation & design program with

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

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

- Can add custom commands to interface Tao with a control system.
- Can be driven by Python



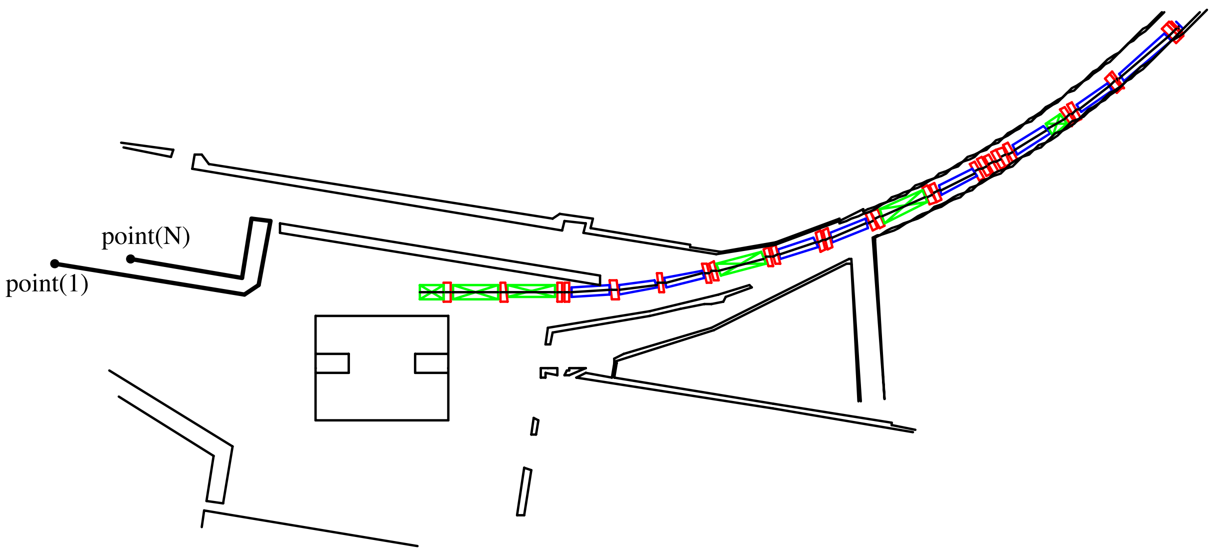

model — tao — 150×23

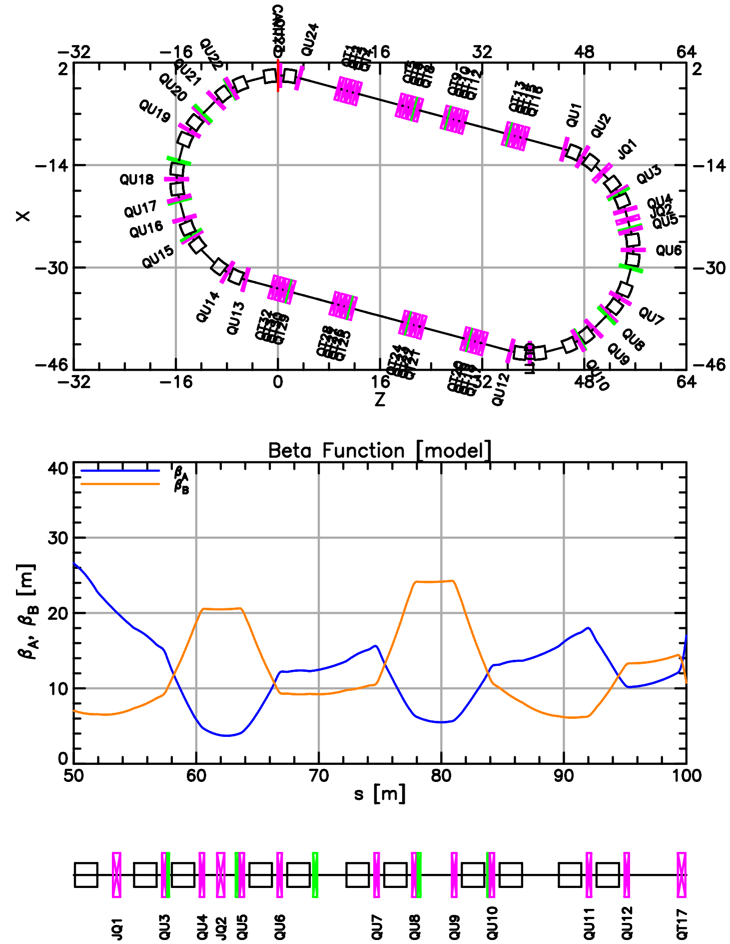
```
 185  FA.PIP06\1#2              Pipe          32.410  0.067   0.33 16.163 -0.01 -12.471   0.30 19.346  0.00  0.000  Alive
 186  FA.CELL04.MAR.BEG\1       Marker        32.410  0.000   0.33 16.163 -0.01 -12.471   0.30 19.346  0.00  0.000  Alive
 187  FA.PIP07\1#1              Pipe          32.466  0.056   0.67 16.285 -0.01 -19.060   0.13 19.635  0.00  0.000  Alive
 188  FA.PIP07\FA.QUA07\1       Quadrupole    32.510  0.044   0.90 16.349 -0.00 -22.819   0.10 19.981  0.00  0.000  Alive
 189  FA.BPM04\1                Instrument    32.510  0.000   0.90 16.349 -0.00 -22.819   0.10 19.981  0.00  0.000  Alive
 190  FA.PIP07\FA.QUA07\1       Quadrupole    32.599  0.089   0.57 16.469 -0.01 -19.269   0.20 20.664  0.00  0.000  Alive
 191  FA.PIP07\1#2              Pipe          32.611  0.012   0.48 16.493 -0.01 -17.887   0.25 20.718  0.00  0.000  Alive
 192  FA.PATCH07\1              Patch         32.611  0.000   0.49 16.491 -0.01 -17.995   0.24 20.715  0.00  0.000  Alive
 193  FA.BLK04\1                Pipe          32.653  0.042   0.24 16.620 -0.01 -11.290   0.47 20.841  0.00  0.000  Alive
 194  FA.PATCH08\1              Patch         32.653  0.000   0.24 16.617 -0.01 -11.380   0.46 20.840  0.00  0.000  Alive
 195  FA.PIP08\1#1              Pipe          32.665  0.012   0.19 16.678 -0.02  -8.923   0.54 20.865  0.00  0.000  Alive
 196  FA.PIP08\FA.QUA08\1       Quadrupole    32.787  0.122   0.10 18.079 -0.02  -4.589   0.62 21.045  0.00  0.000  Alive
 197  FA.PIP08\1#2              Pipe          32.854  0.067   0.33 18.472 -0.01 -12.471   0.30 21.203  0.00  0.000  Alive
 198  FA.CELL05.MAR.BEG\1       Marker        32.854  0.000   0.33 18.472 -0.01 -12.471   0.30 21.203  0.00  0.000  Alive
 199  FA.PIP09\1#1              Pipe          32.910  0.056   0.67 18.594 -0.01 -19.060   0.13 21.492  0.00  0.000  Alive
 200  FA.PIP09\FA.QUA09\1       Quadrupole    32.954  0.044   0.90 18.658 -0.00 -22.819   0.10 21.838  0.00  0.000  Alive
Index name                      key                s       l   beta    phi   eta  orbit    beta    phi   eta  orbit   Track_State
                                                                  a      a     a  x [mm]     b      b     b  y [mm]

    Values at End of Element:

NOTE: Since no range given, the number of elements shown is first 200 of 10323

Tao>
```

CBETA 4-pass ERL

Tao [continued]

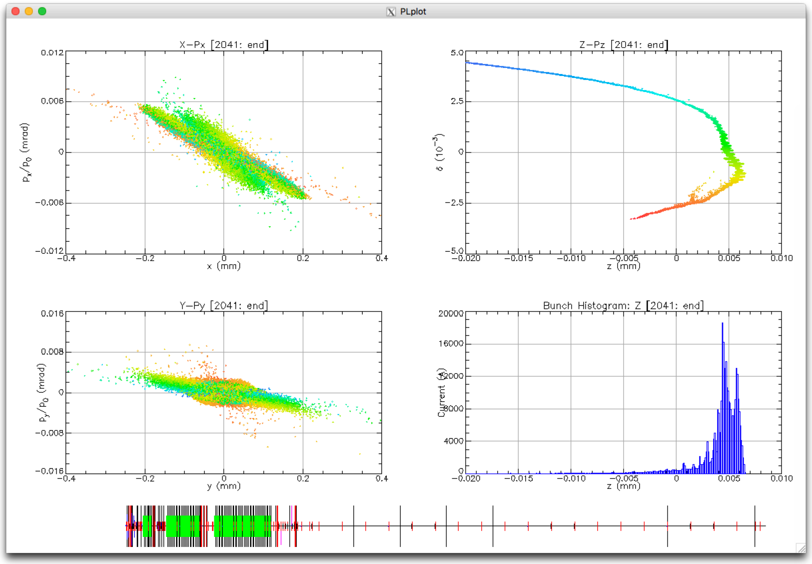
Example: Designing or modifying a machine to be/stay within an existing building:

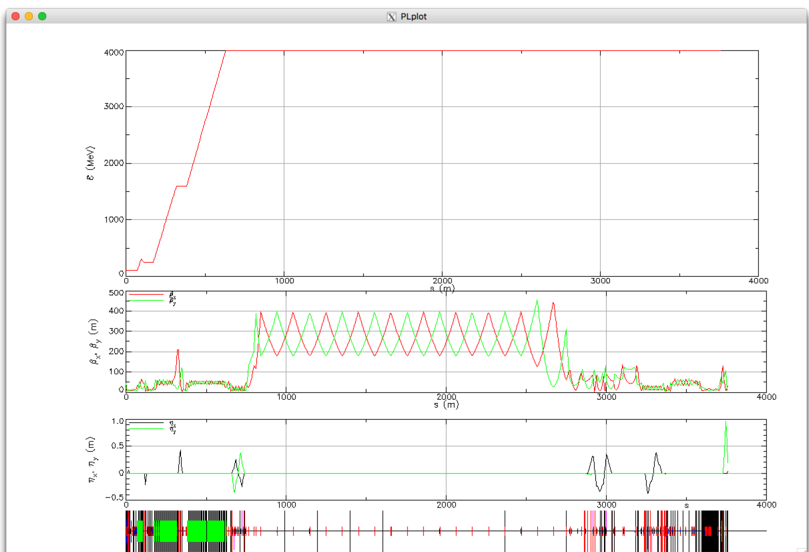




Tao with Bmad gives the flexibility of a library with the convenience of a program.

Tao running the LCLS2 lattice



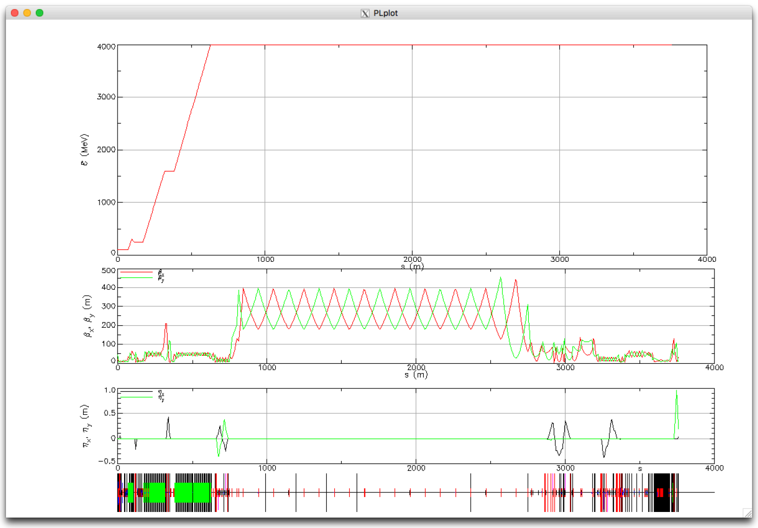


model — tao — 117×64

```
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> |
```

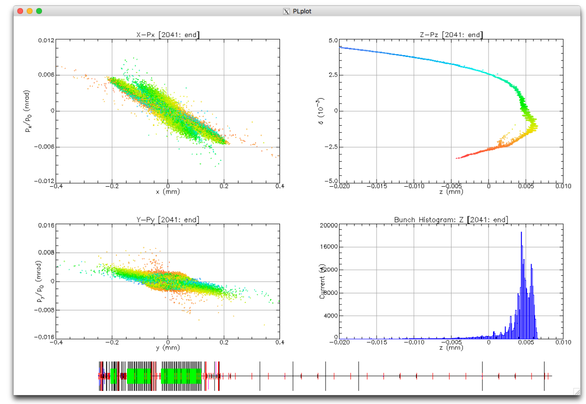
Tao as an online model

Tao Live interactive display




```
Tao> call read_EPICS.tao
     (repeat)
Tao> call write_data.tao
```

CSR, Space Charge tracking




```
Tao> call read_EPICS.tao
     (repeat)
```

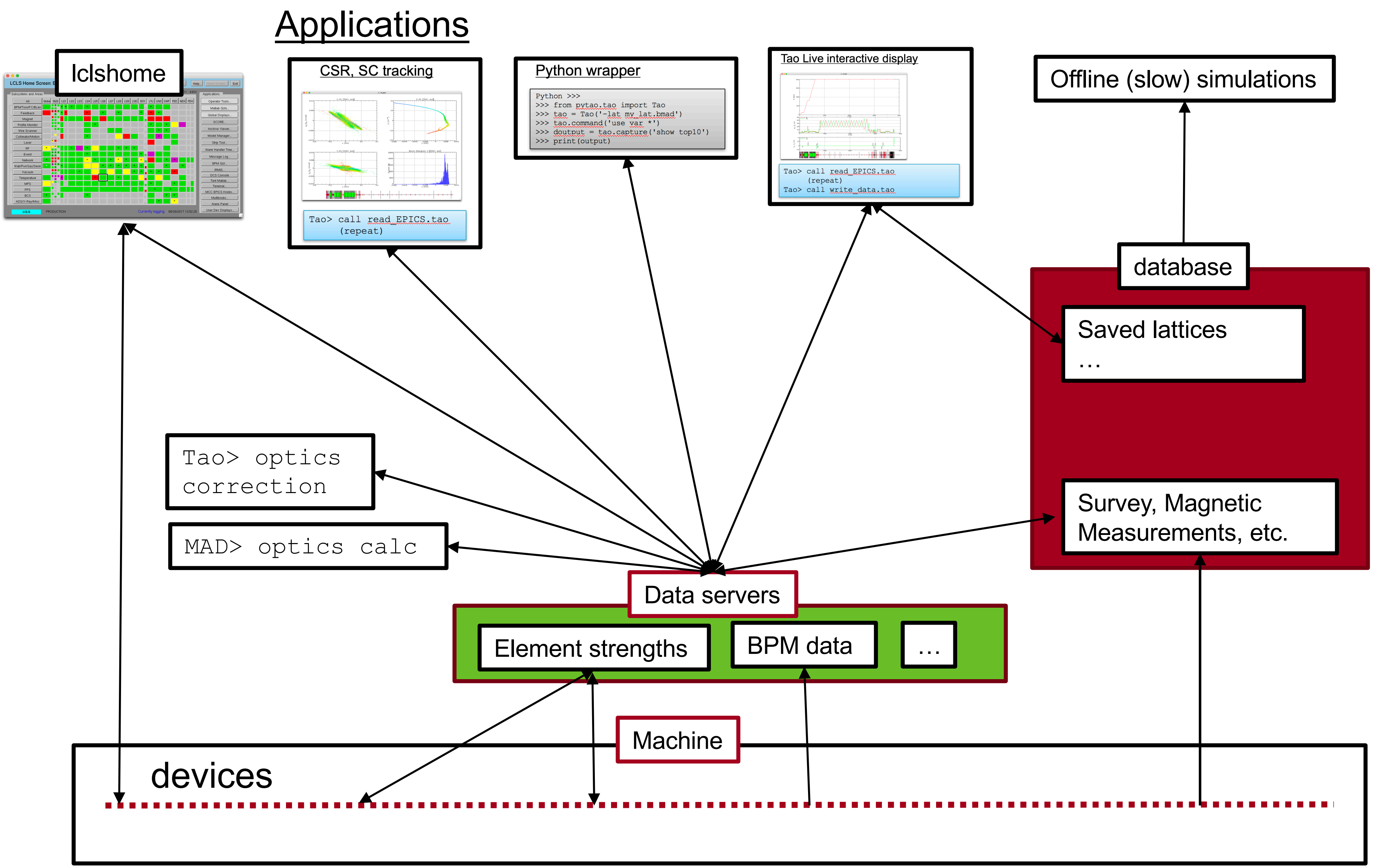
Discover errors

```
Tao> use data bpms
Tao> use variable quad_offsets
Tao> derivative. ! Calculates response of offset quad to BPM
Tao> show derivative

Tao> call read_BPMS_EPICS.tao
Tao> run_optimizer
```

Python wrapper

```
Python >>>
>>> from pytao.tao import Tao
>>> tao = Tao('-lat my_lat.bmad')
>>> tao.command('use var *')
>>> doutput = tao.capture('show top10')
>>> print(output)
```

Architecture



Summary 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

Summary Tao advantages

- Design tool
- Fast online optics calculation
- Multiple optimization methods
- Bunch tracking with CSR, Space charge
- Response of anything to anything: discover quad misalignments
- Built-in plotting
- Customizable via hook routines
- Python interface for automation, advanced GUIs