HOW BMAD (AND PTC) CAN HELP SIMULATE RESONANT DEPOLARIZATION

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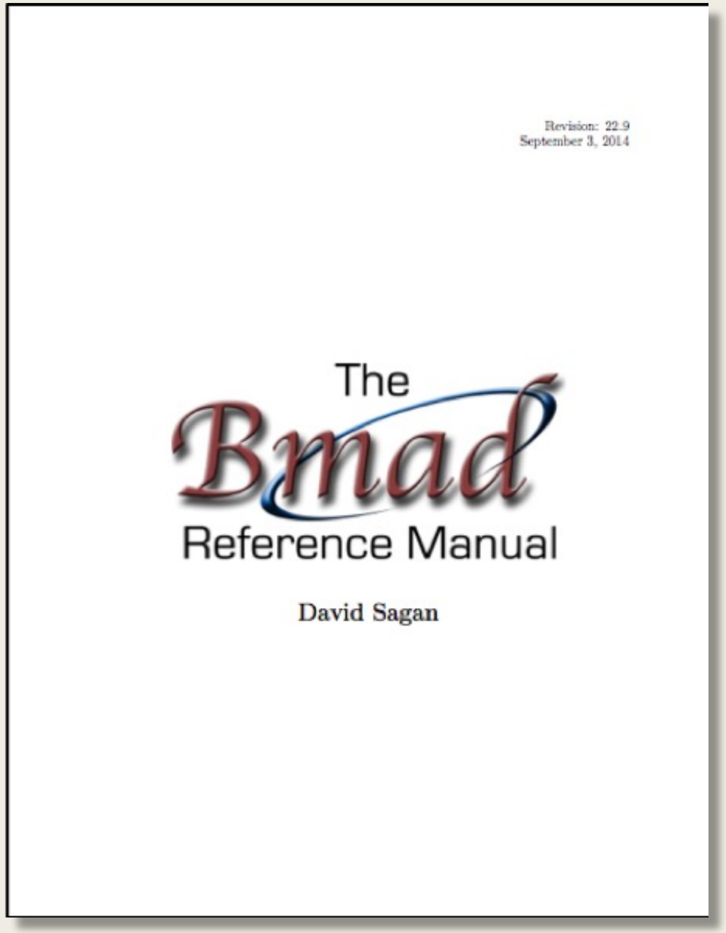
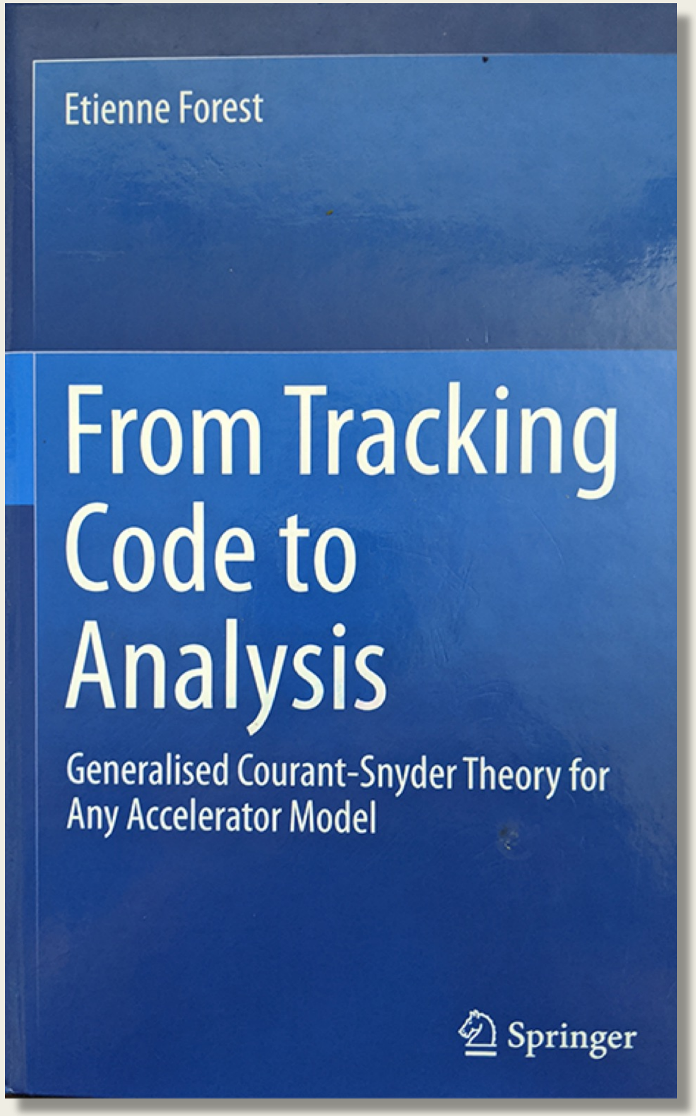


Overview

- **Bmad** is a software library (toolkit) for simulating charged particle beams.
- Written in object-oriented Fortran 2018.
- With certain restrictions, Bmad can be run multi-threaded.
- Lattice files use a MAD like syntax.
- Well documented (Manual is ~600 pages).
- *Open Source:*
  classe.cornell.edu/bmad



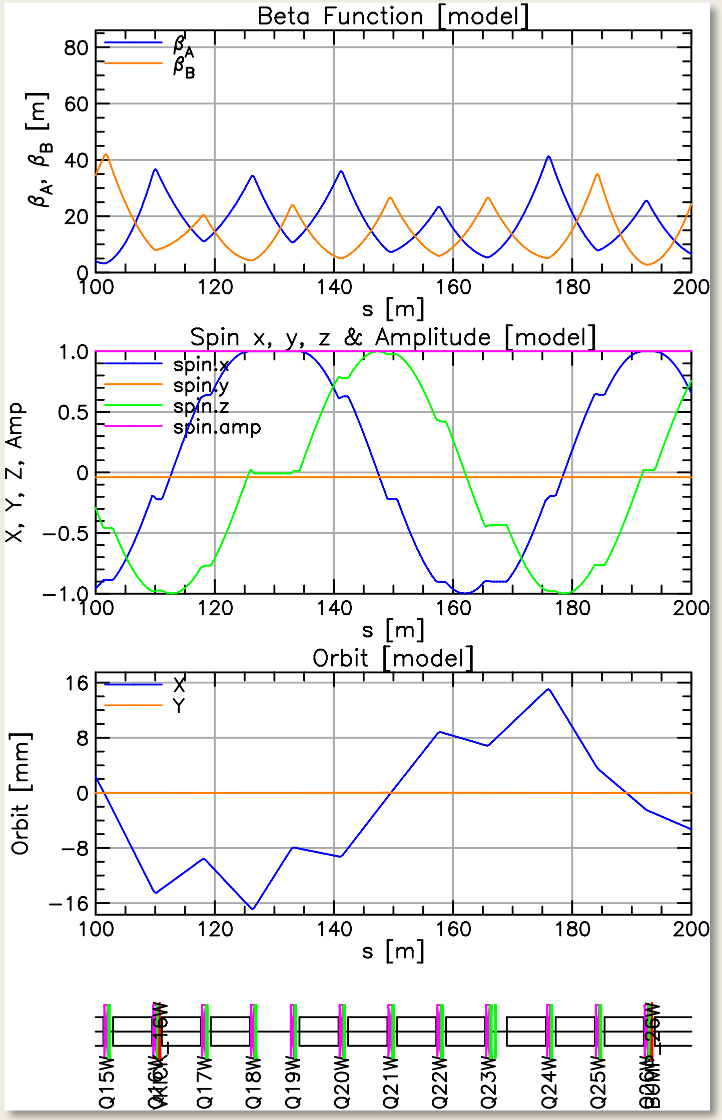
Etienne Forest's FPP/PTC Toolkit

Bmad is interfaced to PTC and is used for:

- *Tracking*
- *Constructing Taylor maps to arbitrary order via symplectic integration.*
- *Normal form analysis to extract:*
  - Resonance strengths.
  - Invariant spin field
  - SLIM G-matrices
  - Nonlinear orbital and spin tunes
  - Etc., etc.

Out	Coef	Exponents
S1:	-0.87067631	0 0 0 0 0 0
S1:	-0.01294703	1 0 0 0 0 0
S1:	-0.00647350	0 1 0 0 0 0
S1:	0.00244198	0 0 0 0 0 1
Sx:	0.01373670	0 0 1 0 0 0
Sx:	0.00686821	0 0 0 1 0 0
Sy:	-0.49185643	0 0 0 0 0 0
Sy:	0.02291863	1 0 0 0 0 0
Sy:	0.01145929	0 1 0 0 0 0
Sy:	-0.00432275	0 0 0 0 0 1
Sz:	-0.00000012	0 0 1 0 0 0
Sz:	0.47801977	0 0 0 1 0 0

Quaternion Spin Map



PTC Integration with Bmad

- Collaboration with Etienne to develop interface routines which allows communication between Bmad and PTC modules.

Example: PTC routines can be used to calculate the 8x8 spin-orbital G-matrix which is used for "spin-matching" lattice design to minimize synchrotron radiation induced depolarization.

```
Tao> show spin -ele Q10W -n 0,1,0 -l 1,0,0   ! G-matrix for Q10W

G-Matrix:
 0.9526    0.5905    0.0000    0.0000    0.0000   -0.0002    0.0000    0.0000
-0.1565    0.9526    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
 0.0000    0.0000    1.0481    0.6095    0.0000   -0.0000    0.0000    0.0000
 0.0000    0.0000    0.1616    1.0481    0.0000   -0.0000    0.0000    0.0000
 0.0000   -0.0002   -0.0000   -0.0000    1.0000    0.0000    0.0000    0.0000
 0.0000    0.0000    0.0000    0.0000    0.0000    1.0000    0.0000    0.0000
 0.0000   -0.0000    0.0335    0.0414    0.0000   -0.0000    1.0000    0.0000
 0.0000   -0.0000   -2.1178   -0.6298    0.0000    0.0000    0.0000    1.0000
```

A Toolkit is like a bunch of Lego blocks

Advantages of a toolkit:

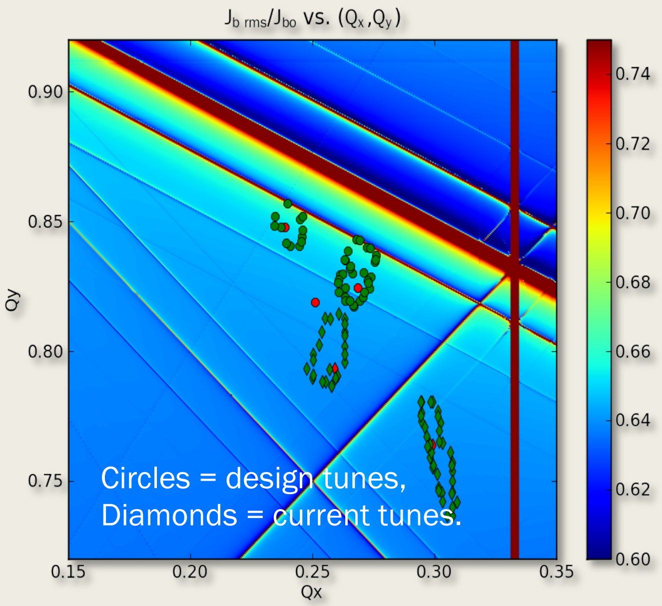
- Cuts down on the *time* needed to develop programs.
- Cuts down on programming *errors* (via module reuse).
- *Standardizes* sharing of lattice information between programs.
- Increased *safety*: Modular code provides a firewall. For example, a buggy module introduced into the toolkit will not affect programs that do not use it.

Bmad Ecosystem

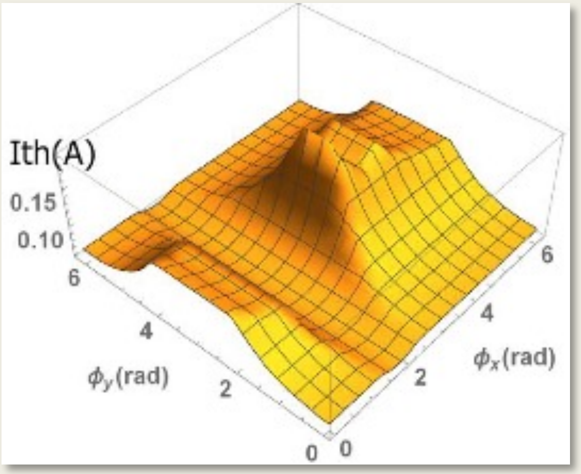
Due to its flexibility, Bmad has been used in a number of programs including:

- **Tao**: General purpose design and simulation program including spin tracking
- **spin_stroboscope**: Spin stroboscopic averaging
- **long_term_tracking**: Multi-turn beam tracking with spin
- **g-2**: Fermilab muon g-2 machine simulation
- **touschek_track**: Tracking of Touschek particles
- **freq_map**: Frequency map analysis
- **MOGA**: Multi-Objective Genetic Algorithm optimization
- **Lux**: Photon tracking in X-ray beam lines
- etc…

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



Tune Scan for CESR Ring Upgrade



BBU threshold current for CBETA as a function of the phase advance between cavities.

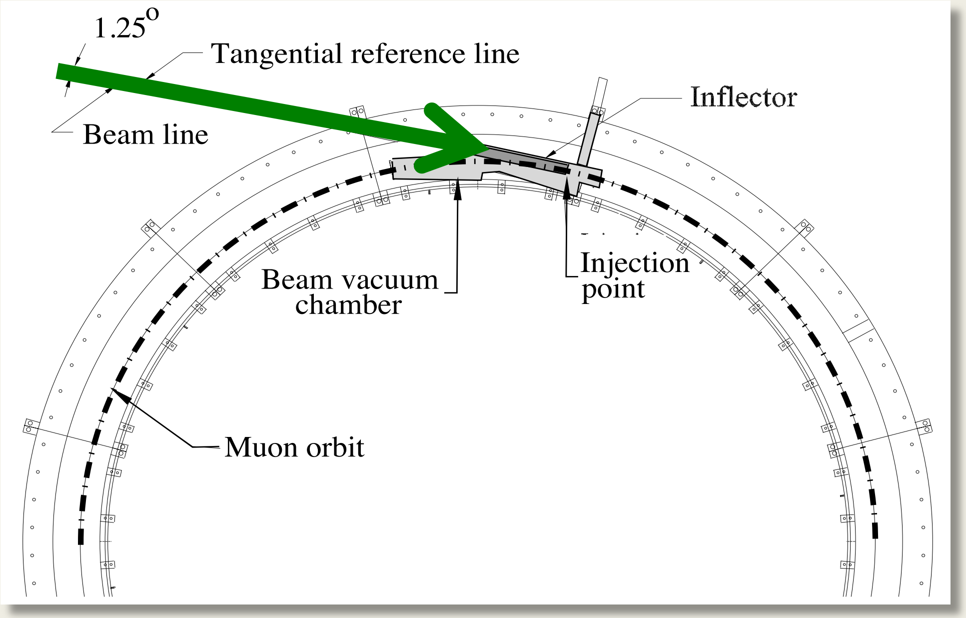
G-2 Simulation Program

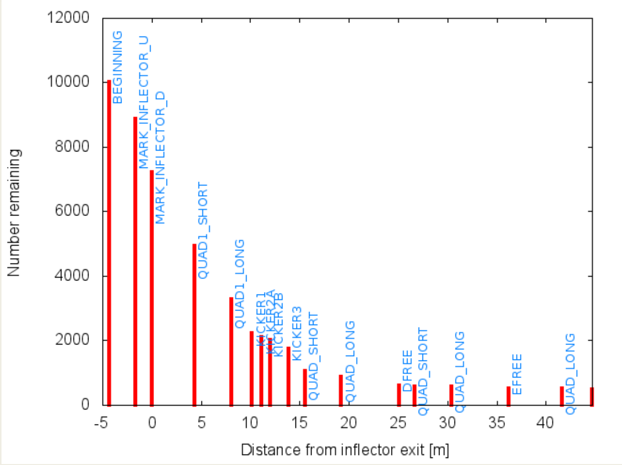
- Dave Rubin at Cornell has been developing a simulation program to simulate the **Muon g-2 experiment** at Fermilab.
- Need to track the polarized muons with:
  - *Injection line into a storage ring.*
  - *Three dimensional field of the injection line.*
  - *Scattering of muons as they cross the inflector wall*
  - *Electrostatic quadrupoles*
  - *Muon decay*
  - *Tracking of electron decay product*

Example of Bmad OOP:

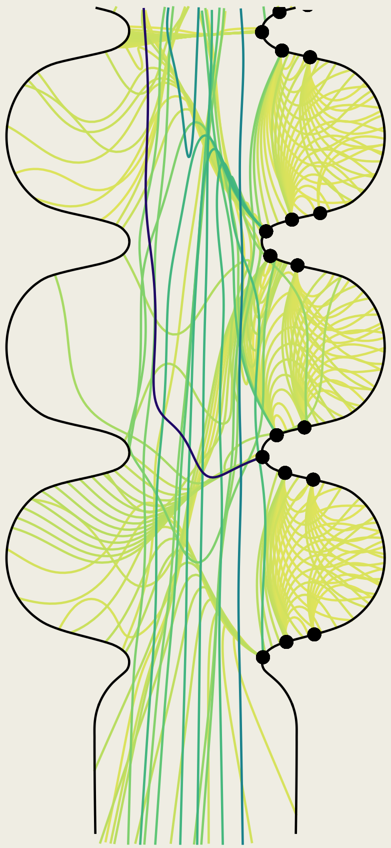
```
type (lat_struct) lat
call bmad_parser (file_name, lat)
call lat_to_ptc_layout (lat)
```

Polarized Muons





Tracking Customization element-by-element



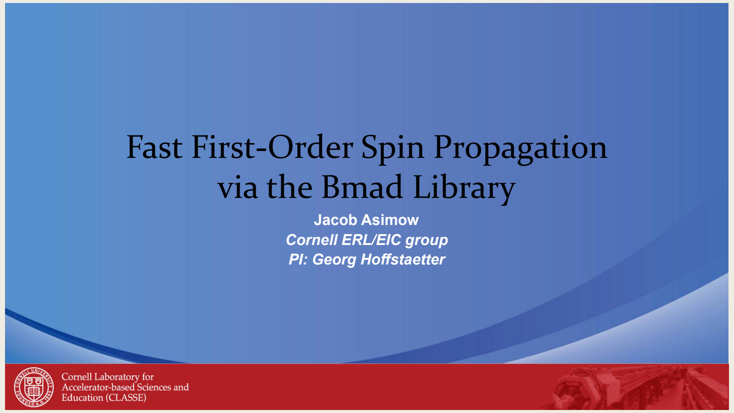
Setting in a lattice file how to track element-by-element:

quad1: quadrupole, l = 0.6, tracking_method = bmad_standard,
spin_tracking_method = sprint, ...

quad2: quadrupole, l = 0.78, tracking_method = taylor, ...

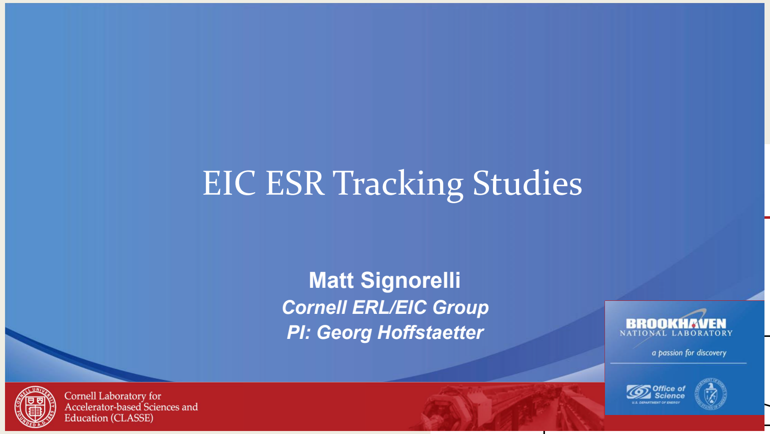
quad3: quadrupole, l = 0.54, tracking_method = custom,
spin_tracking_method = custom, ...

ring: line = (..., quad1, ..., quad2, ..., quad3, ...)



2d FCC Polarization Workshop

Comparing Tracking Methods

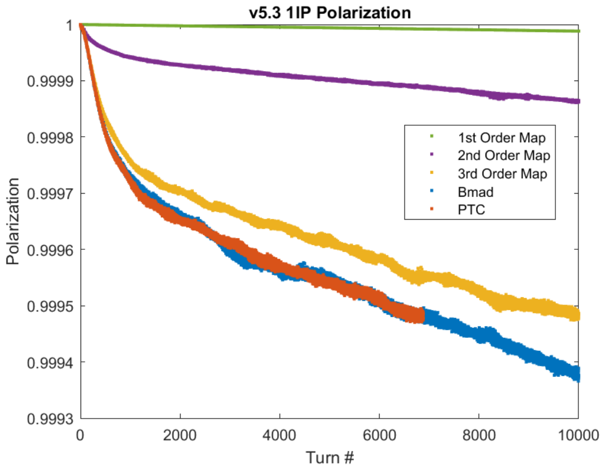


2d FCC Polarization Workshop

Results – v5.3

Brookhaven National Laboratory

	v5.3 1IP	
	τ_{eq} [min]	P_∞
Analytical	31.1	61.3%
1st Order Map Tracking	30.7	66.4%
2nd Order Map Tracking	15.7	33.8%
3rd Order Map Tracking	6.5	14.0%
Bmad Tracking	5.6	12.1%
PTC Tracking	5.7	12.3%



- Polarization significantly worse in nonlinear case
- Such significant damping should not occur if starting w/ equilibrium distribution. Is this a clue on what's happening?

Matt Signorelli (mgs255@cornell.edu) EPOL22 – WP1 – September 21, 2022 16

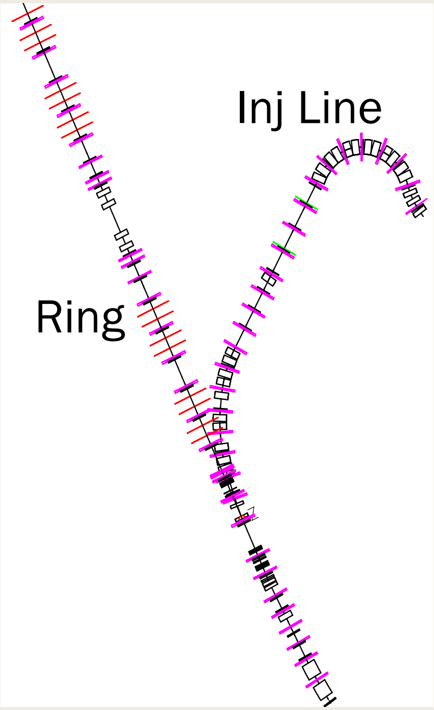
Long_Term_Tracking Program

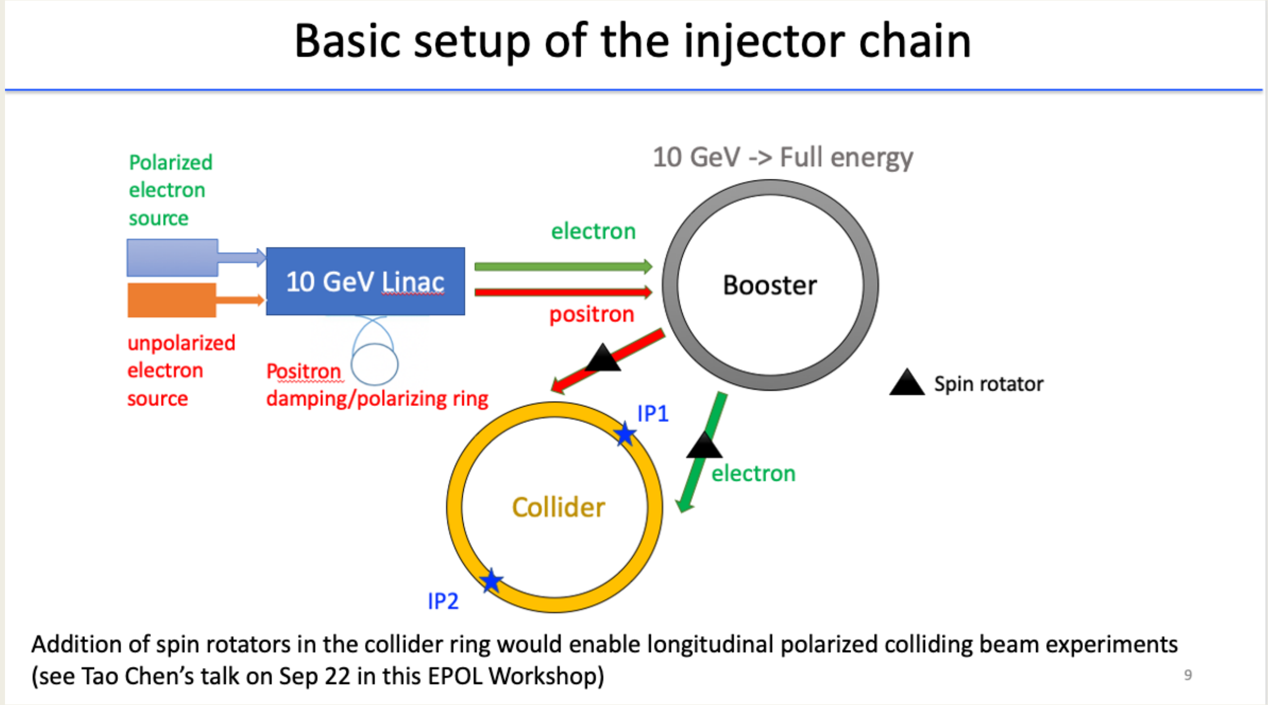
Features:

- Two versions of the program:
  long_term_tracking -- Single threaded
  long_term_tracking_mpi -- Multi threaded
- Transport maps (generated via PTC) can include spin and radiation damping and excitation. Also maps are partially inverted to give symplectic tracking in the limit of zero radiation.
- The lattice can be broken up into sections and different tracking methods can be applied to different sections.
- Element ramping (changing element settings during tracking) is possible. For example, sweeping the frequency of a depolarizer.

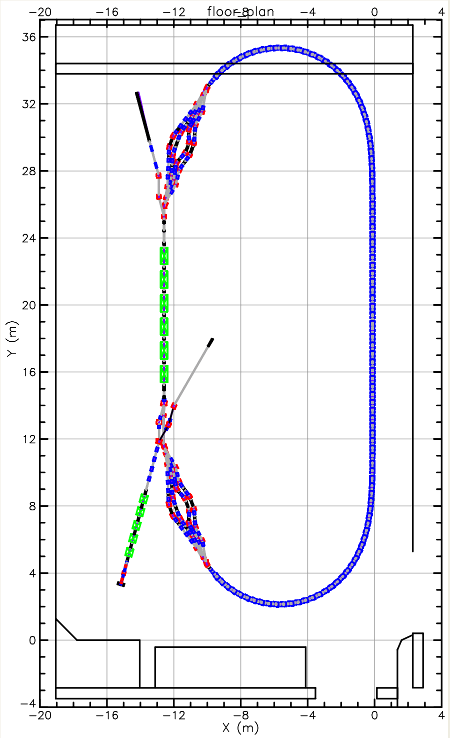
Start to End Simulations

A single Bmad lattice can contain a description of the entire machine from source to collisions for both species.





Zhe Duan "Resonant Depolarization at CEPC" 2d FCC Polarization Workshop



Cornell/BNL 4-pass ERL

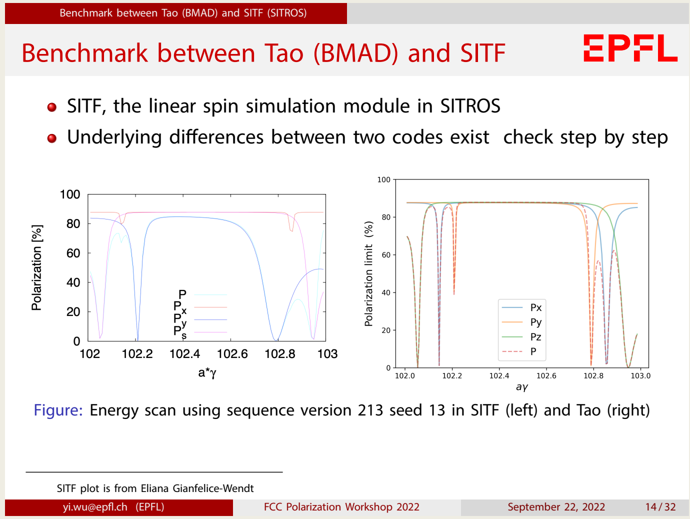
Future

Collaboration to develop spin simulation code:

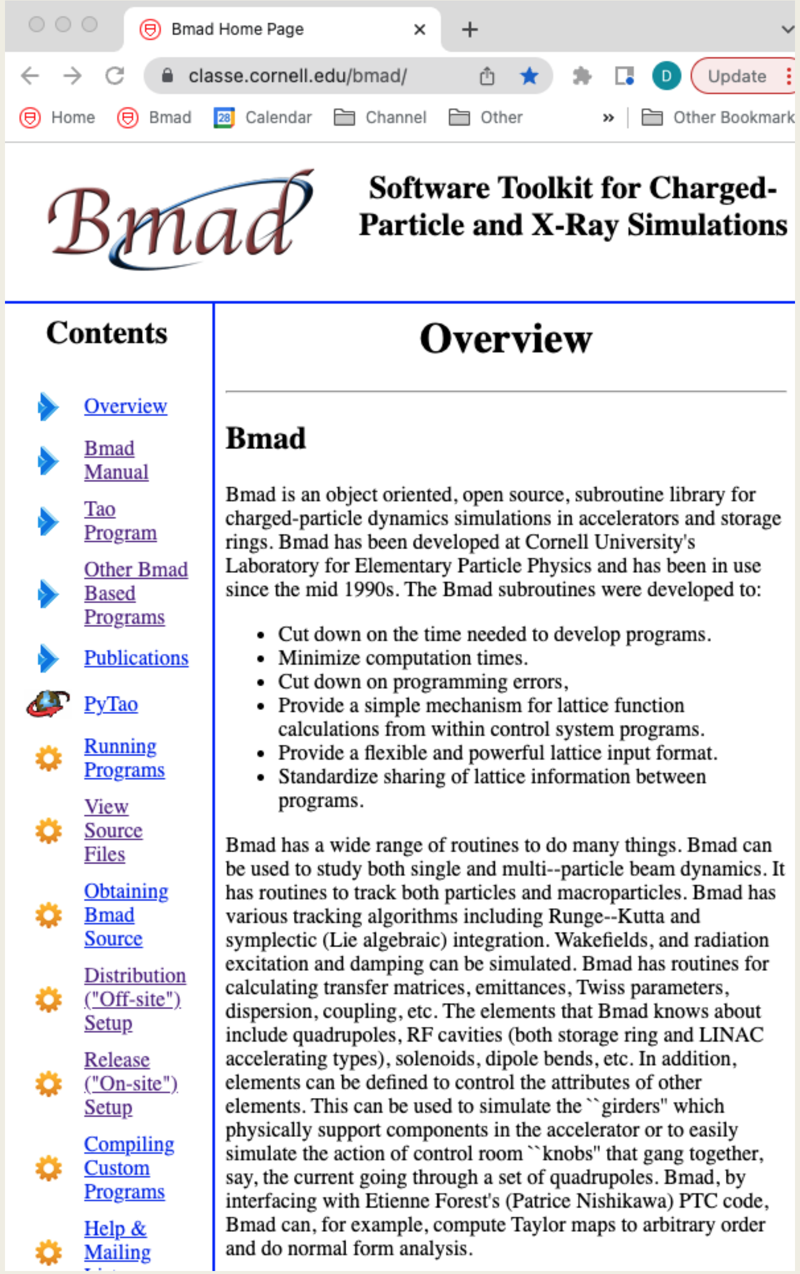
- Desmond Barber (DESY)
- Oleksii Beznosov (Los Alamos)
- Jim Ellison (UNM)
- Klaus Heinemann (UNM)
- Etienne Forest (KEK)
- Georg Hoffstaetter (Cornell)
- David Sagan (Cornell)

Ongoing work:

- EIC/FCC simulations
- Further integration between Bmad and PTC
- Benchmarking with other codes.
- Code speedup (sprint algorithm, etc).
- …etc…



Yi Wu, et. al, "Spin Polarization Simulations for the Future Circular Collider e+e- using BMAD" 2d FCC Polarization Workshop



Bmad Home Page

classe.cornell.edu/bmad/

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Bmad

Software Toolkit for Charged-Particle and X-Ray Simulations

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Overview

Bmad

Bmad is an object oriented, open source, subroutine library for charged-particle dynamics simulations in accelerators and storage rings. Bmad has been developed at Cornell University's Laboratory for Elementary Particle Physics and has been in use since the mid 1990s. The Bmad subroutines were developed to:

- Cut down on the time needed to develop programs.
- Minimize computation times.
- Cut down on programming errors,
- Provide a simple mechanism for lattice function calculations from within control system programs.
- Provide a flexible and powerful lattice input format.
- Standardize sharing of lattice information between programs.

Bmad has a wide range of routines to do many things. Bmad can be used to study both single and multi--particle beam dynamics. It has routines to track both particles and macroparticles. Bmad has various tracking algorithms including Runge--Kutta and symplectic (Lie algebraic) integration. Wakefields, and radiation excitation and damping can be simulated. Bmad has routines for calculating transfer matrices, emittances, Twiss parameters, dispersion, coupling, etc. The elements that Bmad knows about include quadrupoles, RF cavities (both storage ring and LINAC accelerating types), solenoids, dipole bends, etc. In addition, elements can be defined to control the attributes of other elements. This can be used to simulate the ``girders'' which physically support components in the accelerator or to easily simulate the action of control room ``knobs'' that gang together, say, the current going through a set of quadrupoles. Bmad, by interfacing with Etienne Forest's (Patrice Nishikawa) PTC code, Bmad can, for example, compute Taylor maps to arbitrary order and do normal form analysis.

Overview

- Bmad and PTC are open source software libraries for simulating charged particle beams in general and spin in particular.
- Bmad and PTC have many useful features to allow a wide variety of simulations.
- Bmad is useful as a development environment within which new types of simulations can be developed in less time and with less effort and with fewer bugs than starting from scratch. This will be important with new machines like the EIC and FCC which push the envelope to achieve spin polarized beams at greater luminosities and at higher energies.
- Bmad and PTC have been successful due to their modular, object-oriented design which allows adaptation to ever changing simulation needs.
- Bmad and PTC are in continual development.

Thank You!