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Spin Simulations Using the Bmad Toolkit

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In the Beginning…

Brief History:

- 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:

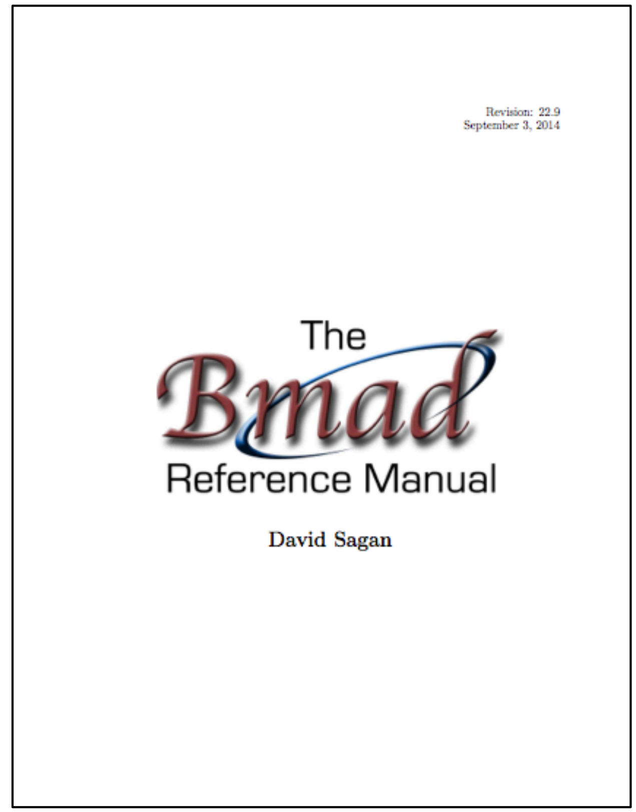
- Lattice design
- X-ray simulations
- Spin tracking
- Wakefields and HOMs
- Beam breakup simulations in ERLs
- Intra-beam scattering (IBS) simulations
- Coherent Synchrotron Radiation (CSR)
- Touschek Simulations
- Frequency map analysis
- Dark current tracking
- Etc., etc.

Overview

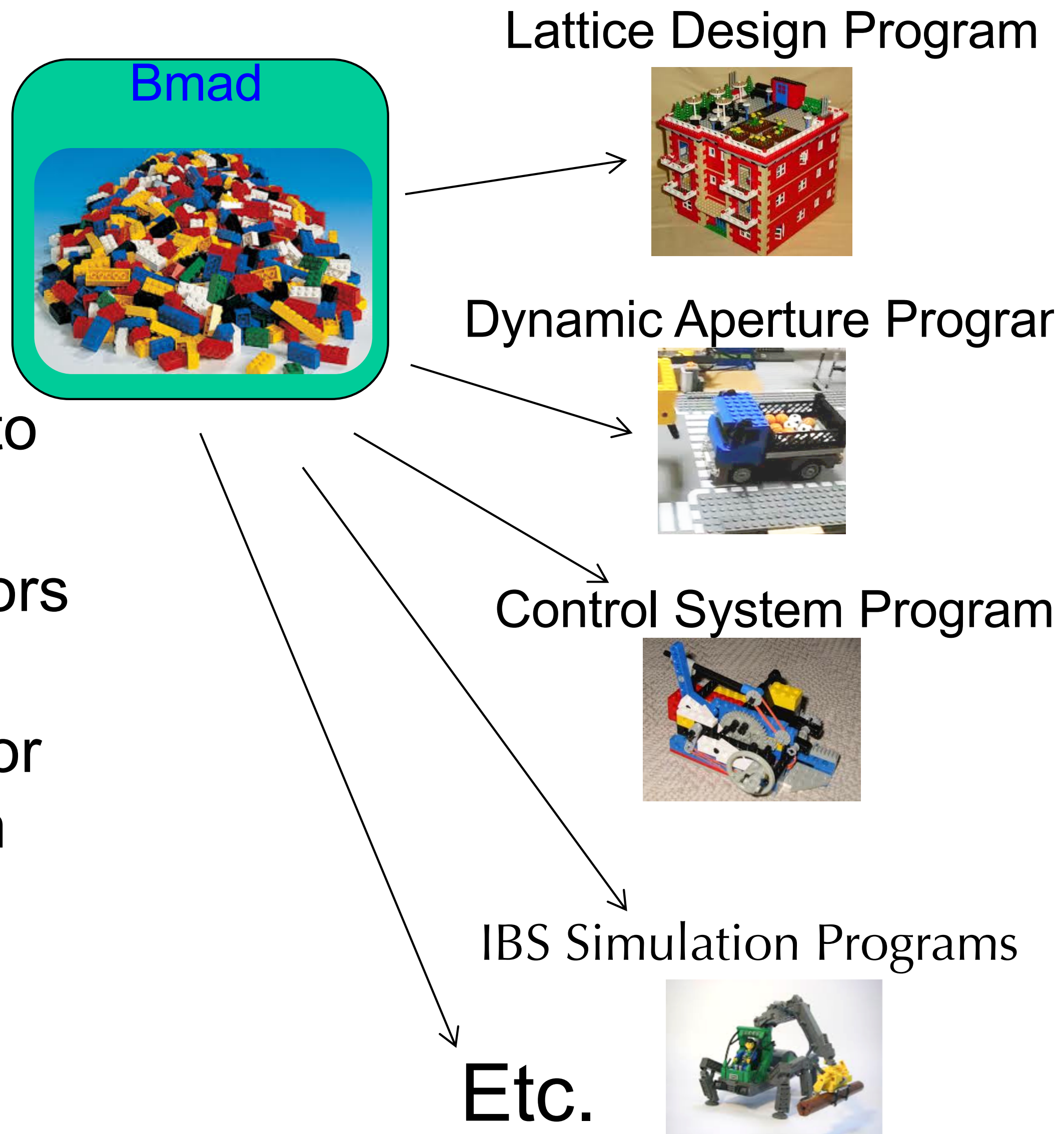
- Written in Fortran 2008.
- Object oriented from the ground up.

```
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



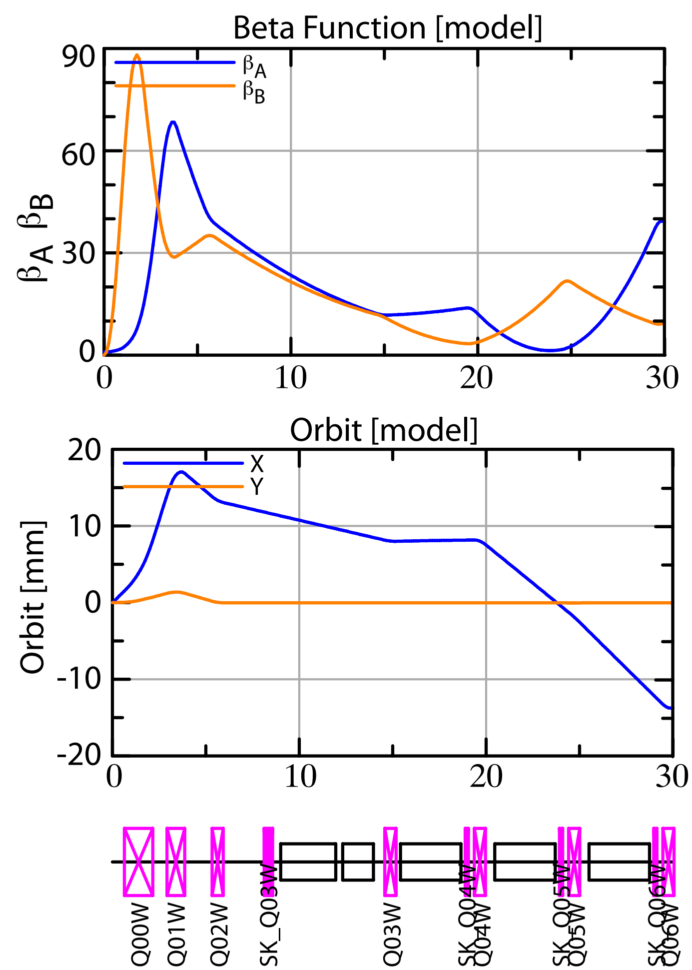
Advantages of a toolkit:

- 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.

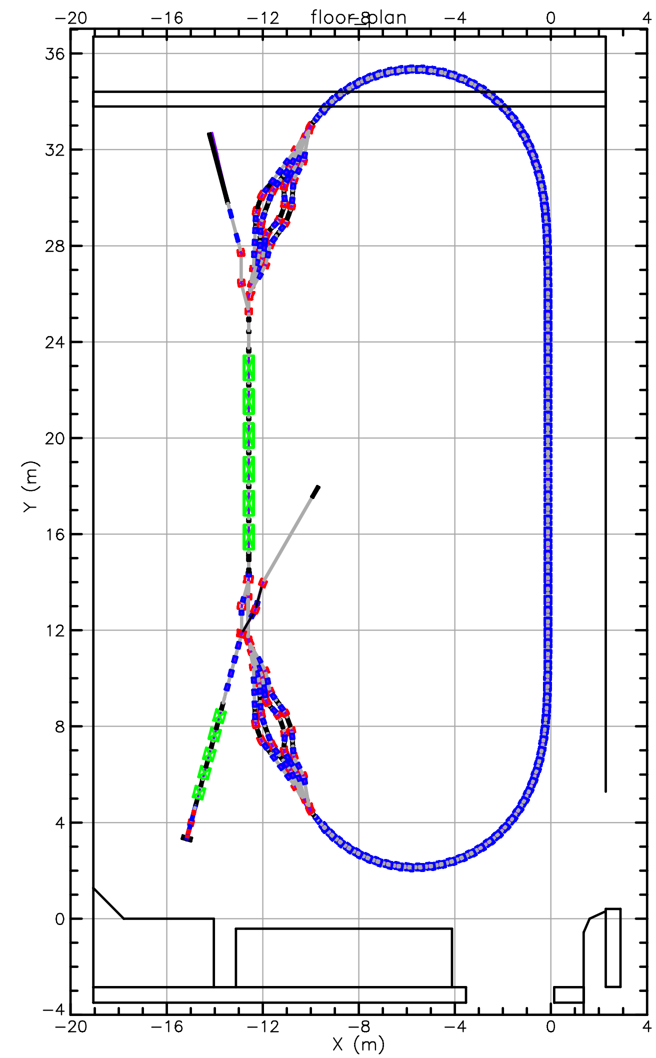
Tao: Tool for Accelerator Optics

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 (like MAD) with
- Twiss and orbit calculations.
- Nonlinear optimization.
- Spin tracking.
- Etc.

Additionally: Tao’s object oriented coding makes it relatively easy to extend it.
- For example: Can add custom tracking code to enable Tao to handle new depolarization effects.

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



Cornell/BNL 4-pass ERL

Spin Tracking

- Bmad can track a particle's spin including EDM and fringe fields.
- Bmad can track the orbit & spin of a particle through arbitrary fields.
- Bmad can produce transfer maps which include spin.

Phase Space Map

	Out	Coef	Exponents	Order
x:	1:	-0.600000000000	0 0 0 0 0 0	0
	1:	1.000000000000	1 0 0 0 0 0	1
	1:	0.145000000000	2 0 0 0 0 0	2
p_x:	2:	-0.185000000000	0 0 0 0 0 0	0
	2:	1.300000000000	0 1 0 0 0 0	1
	2:	3.800000000000	2 0 0 0 0 1	3
y:	3:	1.000000000000	0 0 1 0 0 0	1
	3:	1.600000000000	0 0 0 1 0 0	1
	3:	-11.138187077310	1 0 1 0 0 0	2
p_y:	4:	1.000000000000	0 0 0 1 0 0	1
z:	5:	0.000000000000	0 0 0 0 0 0	0
	5:	0.000001480008	0 1 0 0 0 0	1
	5:	1.000000000000	0 0 0 0 1 0	1
	5:	0.000000000003	0 0 0 0 0 1	1
	5:	0.000000000003	2 0 0 0 0 0	2
p_z:	6:	1.000000000000	0 0 0 0 0 1	1

Spin Map

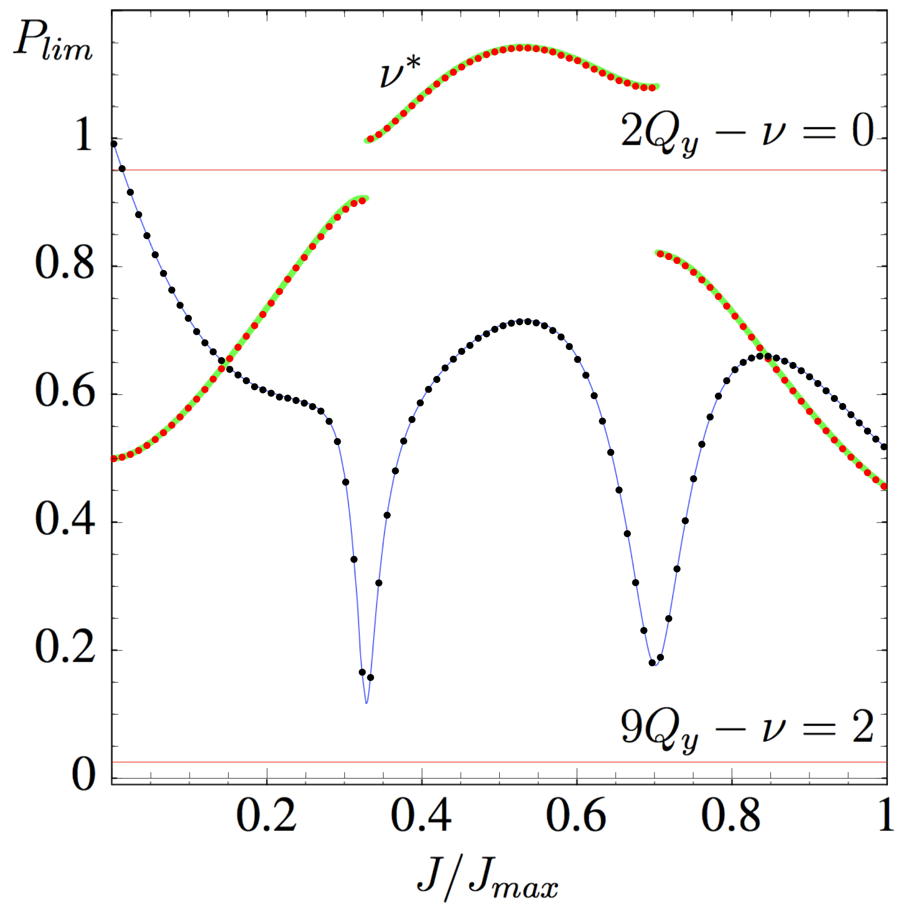
Out	Coef_Sx	Coef_Sy	Coef_Sz	Exponents	Order
Sx:	0.99757886	-0.02372254	-0.06537314	0 0 0 0 0 0	0
Sx:	0.04802411	0.22401654	0.65154583	1 0 0 0 0 0	1
Sx:	0.07391383	3.77338795	-0.24137562	0 1 0 0 0 0	1
Sx:	0.00008802	-0.17584738	0.06515458	0 0 1 0 0 0	1
Sx:	0.01148244	-0.20322945	0.24896717	0 0 0 1 0 0	1
Sx:	-0.00457076	-0.22322148	0.01125358	0 0 0 0 0 1	1
Sy:	-0.02460178	0.75885811	-0.65079114	0 0 0 0 0 0	0
Sy:	0.25039365	-0.04801091	-0.06544895	1 0 0 0 0 0	1
Sy:	-3.02631629	-0.07739091	0.02416143	0 1 0 0 0 0	1
Sy:	0.17584738	0.00008802	-0.00654489	0 0 1 0 0 0	1
Sy:	0.47579058	1.59361755	1.84025908	0 0 0 1 0 0	1
Sy:	0.13046518	-0.46155512	-0.54313051	0 0 0 0 0 1	1
Sz:	0.06504736	0.65082378	0.75643719	0 0 0 0 0 0	0
Sz:	-0.64180483	0.06414595	0.00000000	1 0 0 0 0 0	1
Sz:	-2.27815007	0.22777762	-0.00007328	0 1 0 0 0 0	1
Sz:	0.06515785	-0.00651227	0.00000000	0 0 1 0 0 0	1
Sz:	0.00385332	-1.86555986	1.60475990	0 0 0 1 0 0	1
Sz:	0.11944181	0.53003513	-0.46630288	0 0 0 0 0 1	1

Spin Studies

Bmad has been used for spin simulation studies for:

- Fermilab g-2 ring.
- ILC.
- Julich: Studies for future electric dipole moment (EDM) measurements.
- Spin matching in Jefferson Lab's planned electron ion collider.

Polarization limit P_{lim} and normalized tune ν^* as a function of oscillation amplitude J



Dots: Bmad
Lines: Hoffstaetter [Fig 4.19 "High-Energy Polarized Proton Beams: A Modern View"]

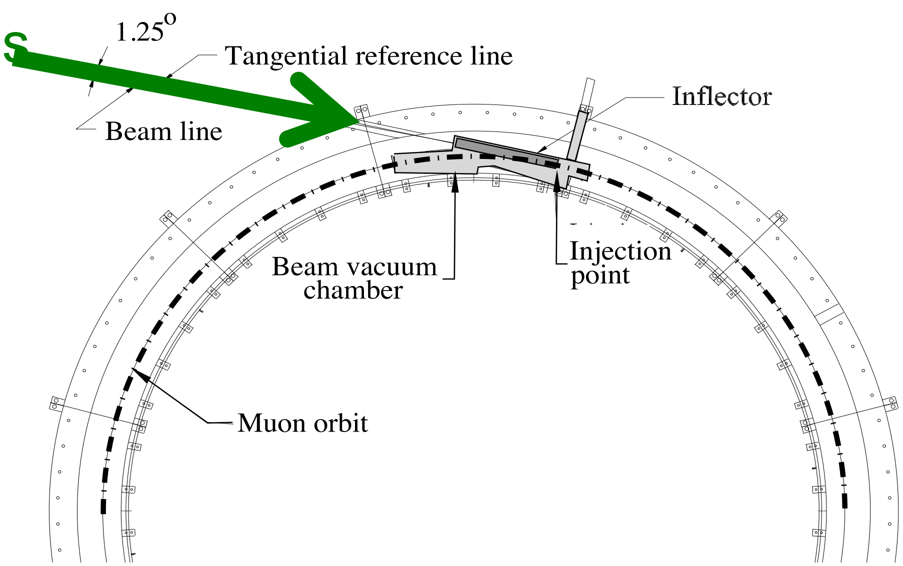
G-2 Experiment

Dave Rubin at Cornell has been developing a simulation program to simulate the Muon g-2 experiment at Fermilab.

Need to simulate:

- Injection line into storage ring.
- Three dimensional field of the injection line.
- Scattering of muons as they cross the inflector wall
- Electrostatic quadrupoles
- Muon decay

Polarized Muons



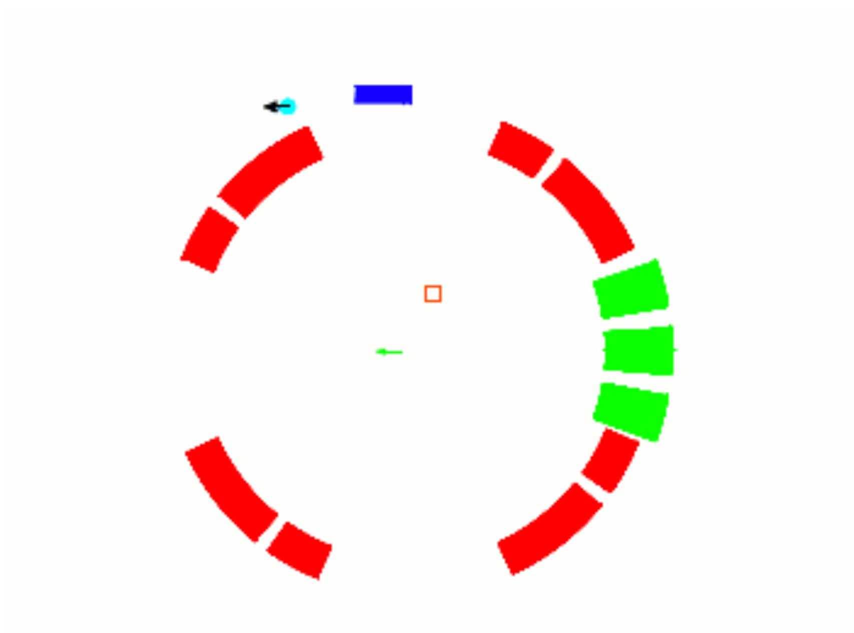
G-2 Simulation

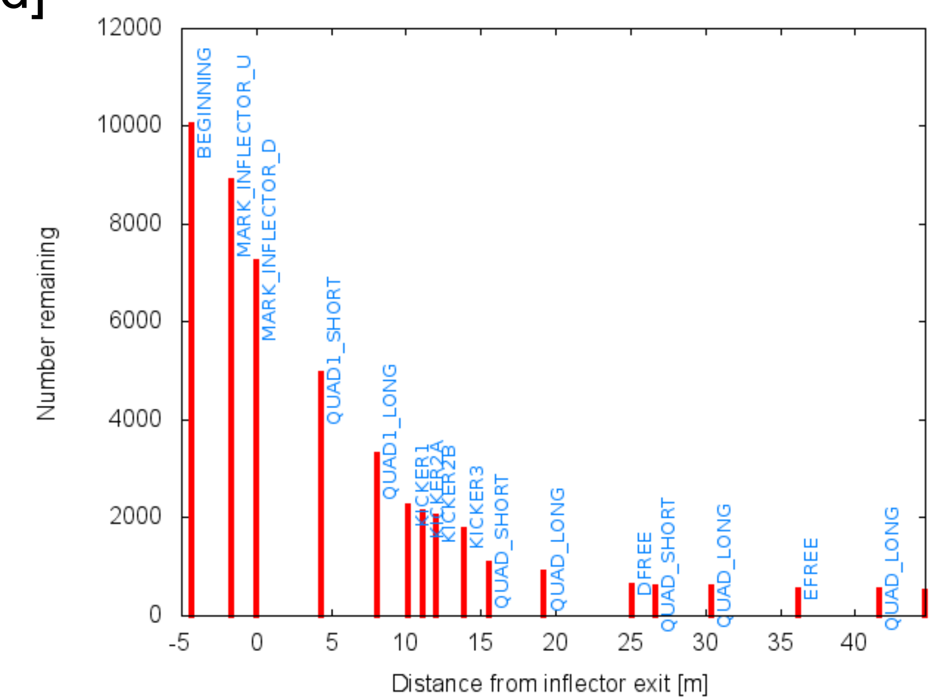
Bmad provides:

- Ability to define the geometry of the injection line and storage ring.
- Ability to define the geometry of the inflector wall.
- Ability to define custom fields for the injection line and electrostatic quads.

Needed to develop for the program:

- Tracking of muons through the inflector wall
- muon decay [will be ported to Bmad]





Conclusions

- Bmad is an open source software library for simulating charged particle beams (and X-rays).
- Bmad can construct symplectic maps with spin for normal form analysis, resonance strength analysis, spin invariant map analysis, analysis of chromatic aberrations, etc.
- Bmad can handle element misalignments, high energy space charge, wakefields, elements with arbitrary fields, etc.
- Bmad can handle complicated lattice geometries such as injection lines, extraction lines, dual ring colliding beam machines, etc.
- Bmad comes with an ecosystem of programs for lattice design, dynamic aperture calculations, Touschek simulation, etc., etc.
- If new types of simulations are needed, with Bmad, new simulation programs can be developed in less time and with less effort and with fewer bugs.
- Bmad has been successful due to it's modular, object-oriented design which allows it to be adapted to ever changing simulation needs.