Bmad for the FCC and Bmad-Julia collaboration for Machine Learning

Georg Hoffstaetter (for Dave Sagan and the Bmad development team)
Cornell ERL / EIC group

June 13, 2024

FCC Week, San Francisco

What is Bmad?

Bmad is an ecosystem of:

- Open-source toolkits (software libraries) and
- Programs constructed with the toolkits.

It has been developed at Cornell for

- The operation of the CESR collider and light source
- The operation of the CBETA ERL
- The design of new accelerators (local and internationally)
- Connection to control systems (e.g., EPICS) for digital twins
- Interactive operations through Python

➔ A large number of features for rings, linacs, ERLs, x-ray lines …

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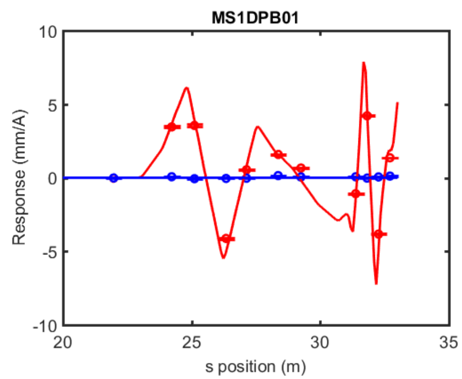
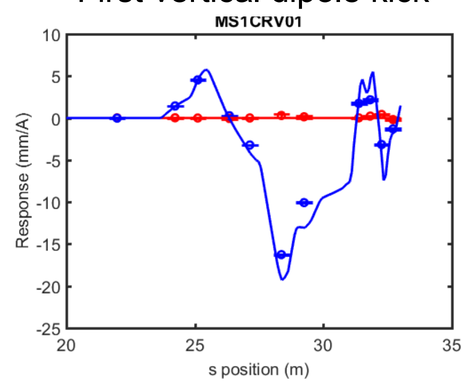
Bmad for digital twins for CESR and CBETA

- CBETA-V: measuring beam trajectories and compare to the digital twin in real time on control-system screens.

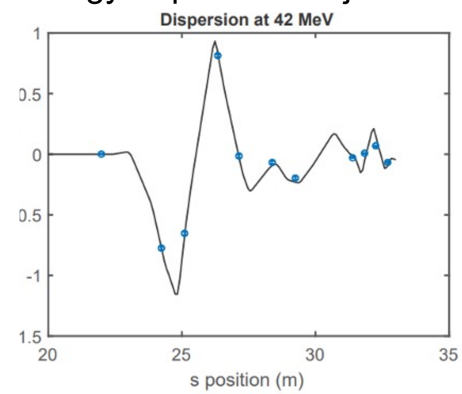
First horizontal dipole kick



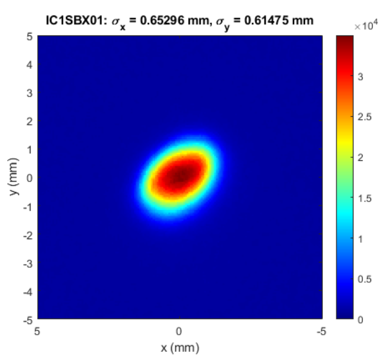
First vertical dipole kick



Energy-dependent trajectories

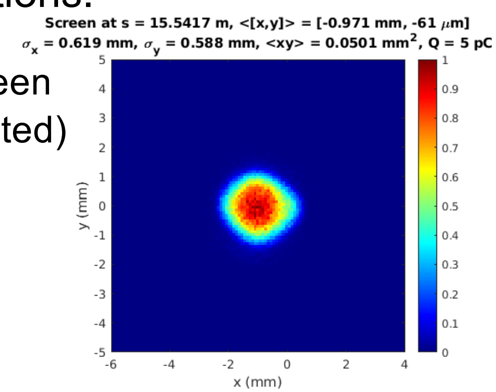


- Measuring bunch profiles and compare in real time with neural network models of slow space-charge calculations.



C1 screen (measured)

C1 screen (simulated)



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Bmad Community

Bmad is open source (hosted on GitHub) and has a thriving community with a SLACK workspace for communication and regular schools and training workshops.

- IPAC'23 and IPAC'24 had Bmad community breakout meetings
- The USPAS graduate class 2023 instructed with Bmad
- Next training workshop at BNL July 29th – August 2 (more than 40 registered)
- Traning workshops envisioned at SLAC 2025 and at USPAS 2026

This has enabled people at numerous labs to be able to use Bmad to simulate many machines:

- ✓ Cornell CESR ring
- ✓ CORNELL CESR injection chain.
- ✓ CBETA - Cornell/BNL ERL
- ✓ CERN FCC
- ✓ CERN LHC
- ✓ Julich COSY ring
- ✓ International Linear Collider (ILC)
- ✓ BNL EIC
- ✓ BNL SSRL
- ✓ BNL RHIC
- ✓ Fermilab G-2
- ✓ Fermilab Main Injector
- ✓ KEK SuperKEK-B
- ✓ SLAC LCLS-II
- ✓ Budker VEPP-4M
- ✓ China CEPC
- ✓ Beijing High Energy Photon Source (HEPS)
- ✓ TRIUMF
- ✓ Spallation Neutron Source (SNS)
- ✓ JLab CEBAF
- ✓ JLab FEL
- ✓ Frascati linear accelerator
- ✓ Paris Synchrotron Soleil
- ✓ ... etc ...

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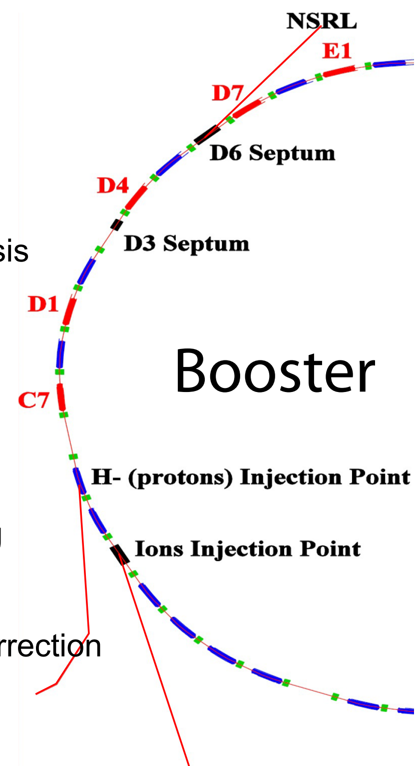
Bmad Simulations

Bmad has been used to study:

- Lattice design
- Space charge simulations including cathode effects.
- Beam breakup (BBU) simulations
- Coherent Synchrotron Radiation (CSR)
- Halo studies
- Microbunching evaluation
- Machine online modeling
- Spin tracking
- Intra Beam Scattering (IBS)
- Touschek scattering
- Wakefields

- Weak-strong beam-beam studies
- Phase noise on Crabbing dynamics
- Feedback systems
- Energy ramping
- Bunch merging
- Electron cooling
- Resonant extraction
- Spin matching
- Spin resonance studies
- Invariant spin field calculations
- Dynamic aperture
- Tune scans plots

- Frequency map analysis
- Long term tracking
- Stripper foils
- Positron converters
- Injection studies
- Cathode laser shaping
- Orbit correction
- Twiss and coupling correction
- X-ray simulations
- Resonance strengths
- Normal form analysis
- Etc., Etc.



Start-to-end simulations: Bmad can simulate an entire accelerator complex including injection lines, extraction lines, dual colliding beam rings, etc.

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What can Bmad contribute to the FCC ?

Addendum to CERN's MOE with Cornell:

WORK UNIT DELIVERABLE	
BB-3/document	**FCC-ee ring beam dynamics**
Cornell's deliverable:	**Report on electron self polarization in the main ring** **Report on dynamic aperture optimizaitons in the main ring** **Progress report on a Machine Learning oriented accelerator code**
Required delivery date:	One year after funding start – e.g., October 1, 2024 if funding starts this September.
CERN's support (if any is required)	None
Required support date:	
Acceptance:	Michael Benedickt (CERN)

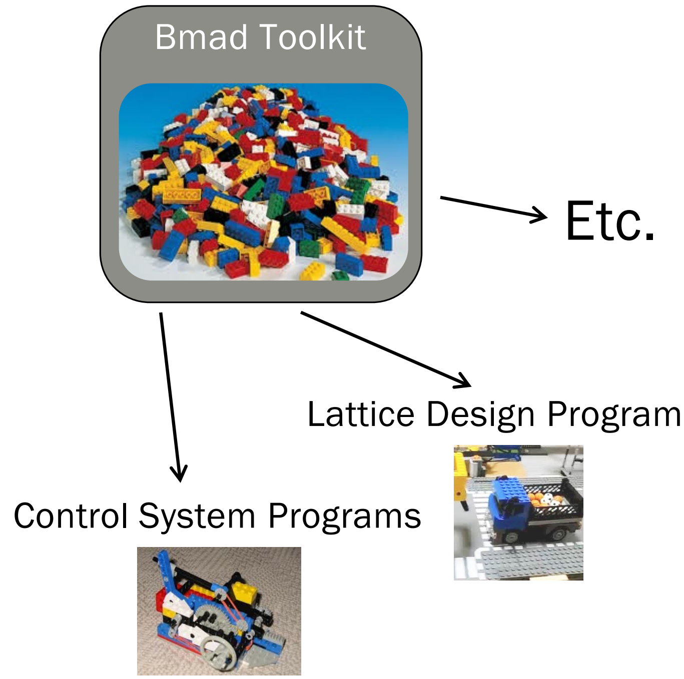
See strength and breadth of Bmad on the example of work of the Cornell's ERL/EIC group

Bmad Toolkits

How can Bmad simulate so many different things?

Compared to developing from scratch, the Bmad toolkits allow for the development of simulation programs

- ✓ In less time
- ✓ With fewer bugs (due to module reuse).
- ✓ Enable inter-program data communication (via common lattice and beam format, and other standardizations).
- ✓ Since programs are modular it is easier to adapt them to meet changing simulation needs



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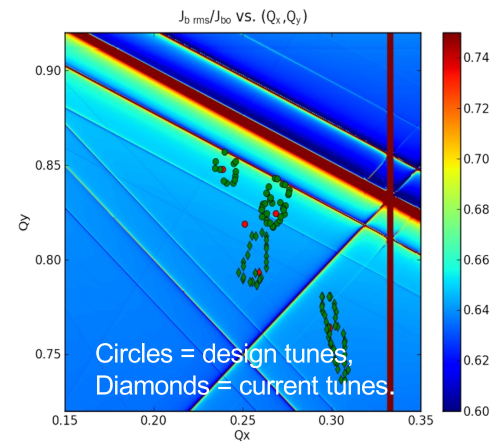
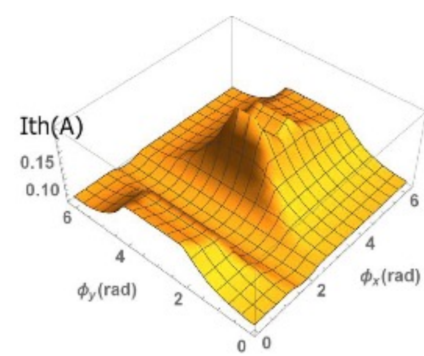
Bmad Programs

As a result of Bmad's modular structure, a number of simulation programs that use Bmad have been developed:

- ✓ Tao -- General purpose simulation program
- ✓ long_term_tracking -- Long term tracking program
- ✓ dynamic_aperture -- Dynamic aperture program
- ✓ CesrV -- Digital Twin for the Cornell CESR storage ring.
- ✓ CBETA-V -- Digital Twin for the Cornell/BNL CBETA ERL
- ✓ bbu -- RF cavity induced beam breakup instability
- ✓ synrad3d -- Synch X-rays tracking within a vac chamber.
- ✓ dynamic_aperture -- Dynamic aperture program
- ✓ ibs_ring -- Intra beam scattering
- ✓ tune_scan -- Tune plane scan
- ✓ And many more...



Tune Scan for CESR Ring Upgrade



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

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Breadth of Bmad Capabilities

Wikipedia
The Free Encyclopedia

Accelerator physics codes

The Bmad ecosystem of toolkits and programs is unique among all accelerator simulation codes.

This has enabled Bmad, of all simulation codes, to have the greatest range of capabilities and allows Bmad to do simulations not possible with other codes.

Simulation Code	Single Particle	Spin Tracking	Taylor Maps	Beam-Beam Interaction	Electromagnetic Field Tracking	Collective Effects	Synchrotron Radiation	Radiation Tracking	Wakefields	Extensible
Accelerator Toolbox (AT),[6]	Yes	Yes[7]	No	No	No	Yes	No	No	No	Yes
ASTRA[8]	Yes	No	No	No	Yes	Yes	No	No	Yes	No
BDSIM[9]	Yes	No	No	No	Yes	No	No	No	No	Yes
Bmad [10]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
COSY INFINITY[11]	Yes	Yes	Yes	No	Yes	No	No	No	No	No
DYNAC[12]	Yes	No	No	No	No	No	No	No	No	No
Elegant[13]	Yes	No	No	No	Yes	Yes	Yes	No	Yes	No
MAD8 / MAD-X	Yes	No	Yes	Yes	No	No	Yes	No	No	No
MAD-NG[14]	Yes	No	Yes	Yes	No	No	Yes	No	No	Yes
MERLIN++[15][16]	Yes	Yes	No	No	No	No	No	No	Yes	Yes
OCELOT[17]	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
OPA[18]	Yes	No	No	No	No	No	No	No	No	No
OPAL[19]	Yes	No	Yes	No	Yes	Yes	No	No	Yes	Yes
PLACET[20]	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes
Propaga[21]	Yes	No	No	No	No	No	No	No	No	Yes
PTC[22]	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes
SAD[23]	Yes	No	No	Yes	No	Yes	Yes	No	Yes	No
SAMM[24]	Yes	Yes	No	No	No	No	No	No	No	No
SixTrack[25]	Yes	No	Yes	Yes	No	No	No	No	No	No
Zgoubi[26][27]	Yes	Yes	No	No	Yes	No	Yes	No	No	Yes

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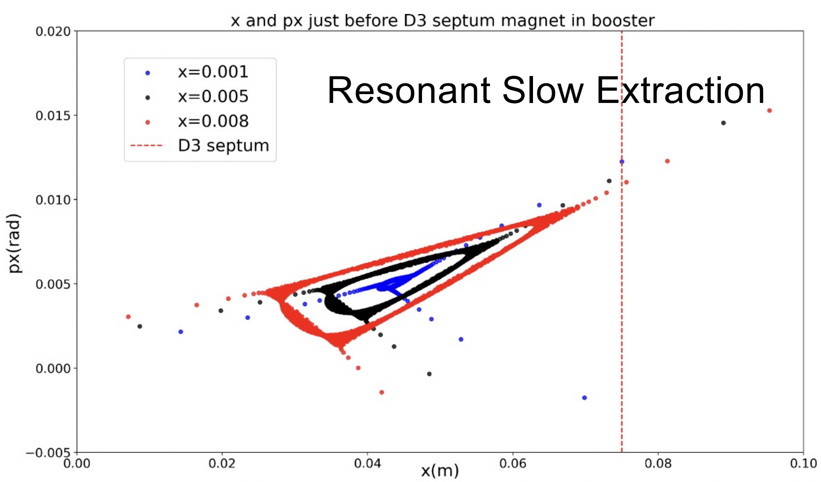
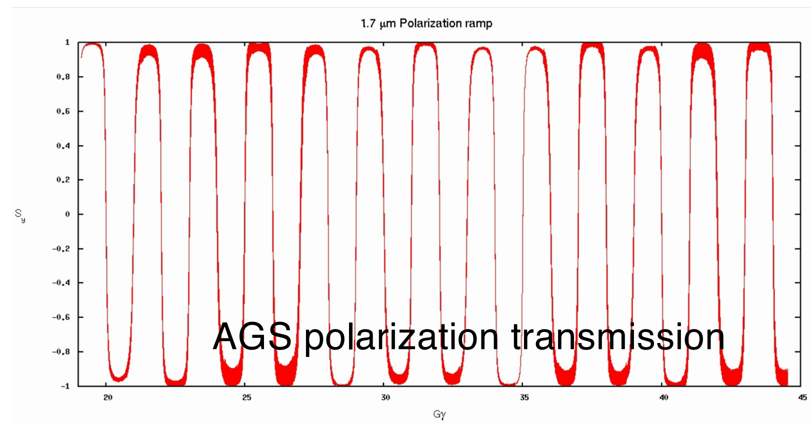
Slow Extraction and AGS Polarization

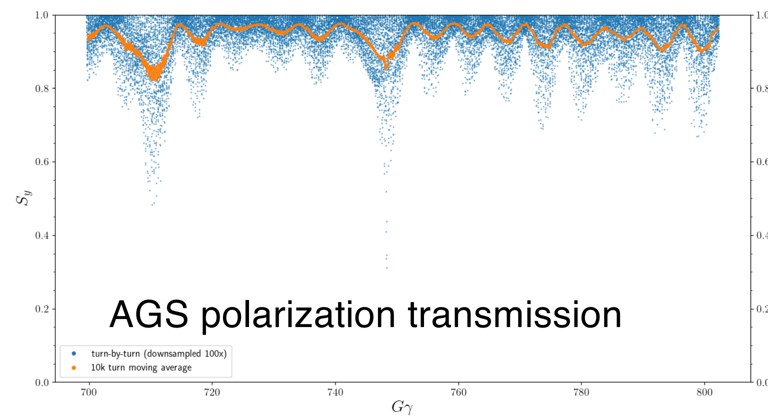
Bmad used for:

- Booster -> NSRL slow extraction
- AGS polarization transmission

  -- Eiad Hamwi, Cornell







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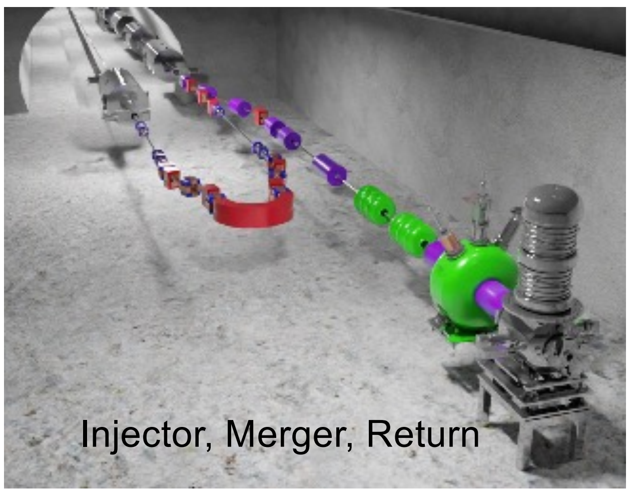
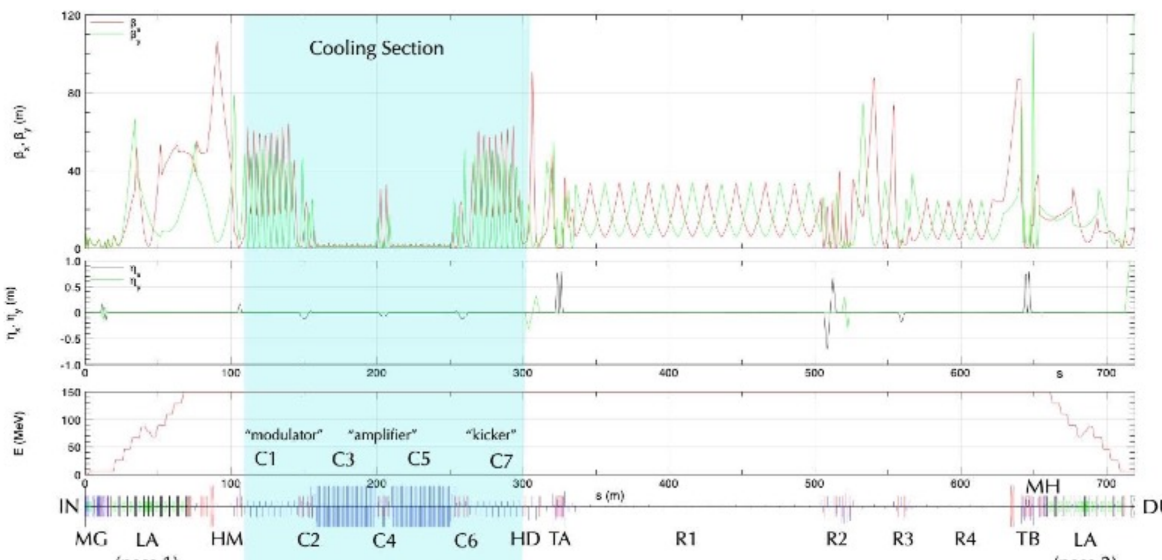
ERL Cooler

- Bmad used extensively for Xelera's SBIR project (through Phase II) to design the EIC ERL cooler, including the precooler.
- Bmad was used for the injector as well as the main lattice, including the ERL multipass optics and start-to-end simulations.

-- Chris Mayes, Xelera Research LLC.



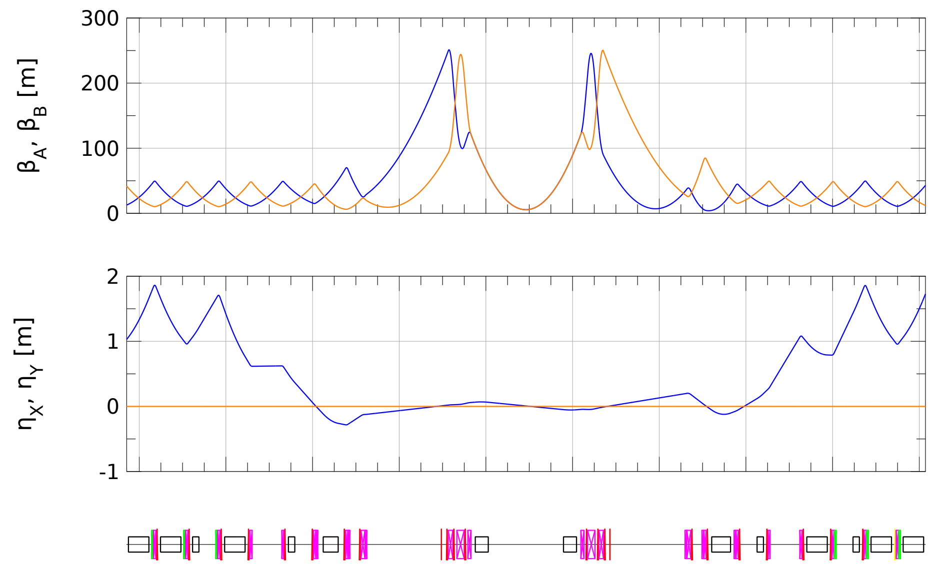


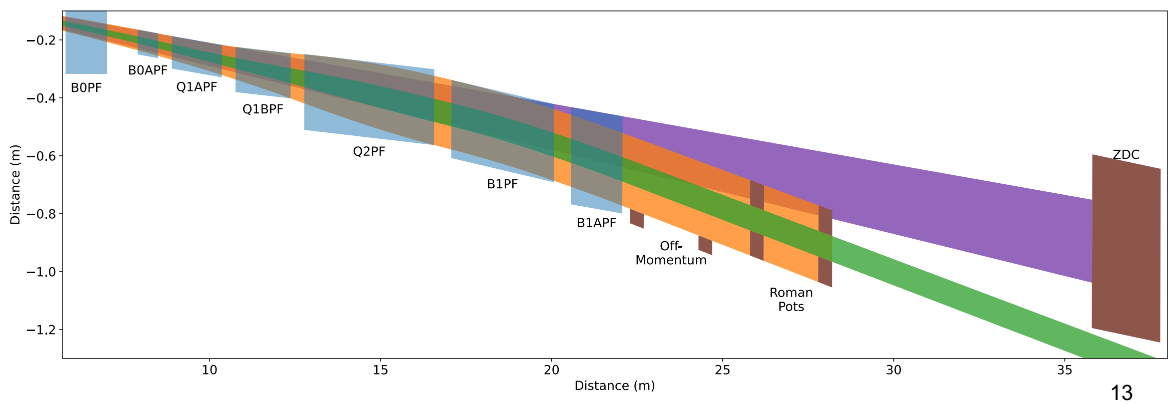
Lattice Design

Bmad used for:

- Interaction region design (ESR and HSR, layout, matching)
- HSR ring design
- Superbend calculations in the ESR (emittance and excursion vs. lengths of dipoles)

-- Scott Berg, BNL

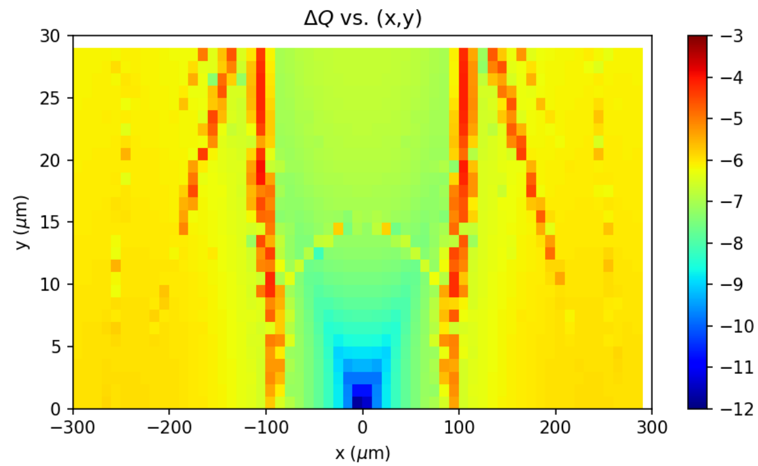


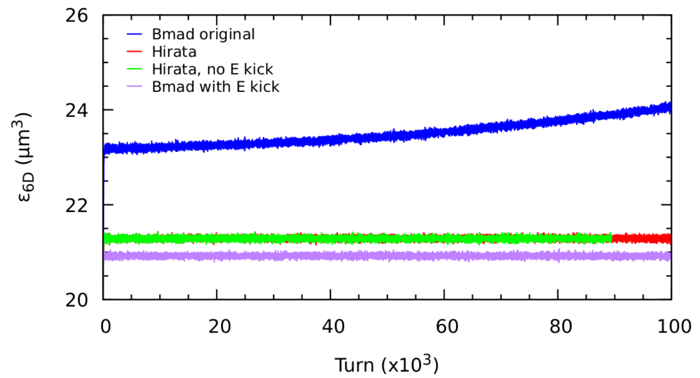


Effects of Phase Noise and the Beam-Beam Interaction on Crabbing Dynamics

“Theory predicts rather tight tolerances on crab cavities' phase noise. Bmad simulations were benchmarked against and confirmed the theory. Bmad is presently being used to study the effect of beam-beam interaction on the crabbing dynamics in the presence of noise and to develop and verify a feedback system. Bmad is one of the few or possibly even the only general-purpose beam dynamics code that allows for a straightforward modeling of these mechanisms. In fact, Bmad is unique in that its beam-beam model accounts for a time-dependent beam-beam effect not accounted for by any other code. A paper on this aspect is to be published.”

-- Vasiliy Morozov, ORNAL

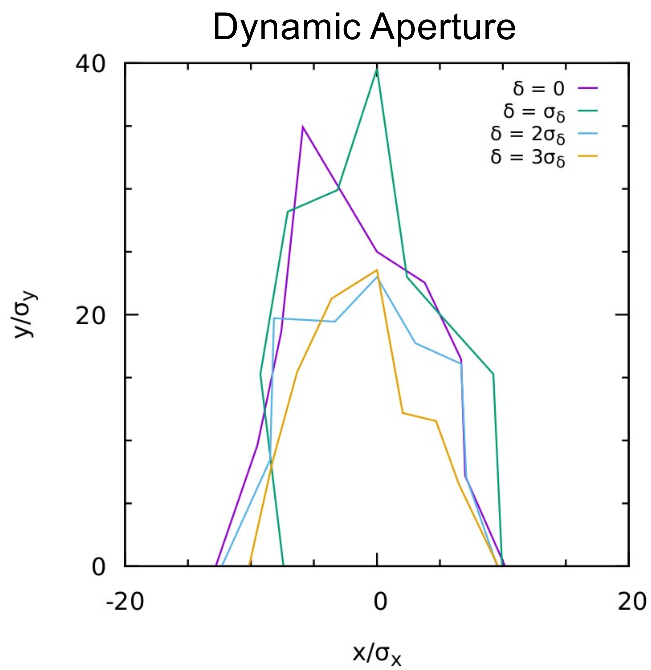




Detector Solenoid Integration in the ESR and HSR

"Detector solenoid integration faces unique requirements at the EIC due to a large beam crossing angle and a tilt of the ESR plane. One has to simultaneously account for orbit excursion, transverse and longitudinal coupling, optics and polarization. Unlike most other codes, Bmad has the tools to consider and correct all of these aspects at the same time. These tools greatly simplify integration of correction elements, design optimization and visualization of the results."

-- Vasiliy Morozov, ORNAL



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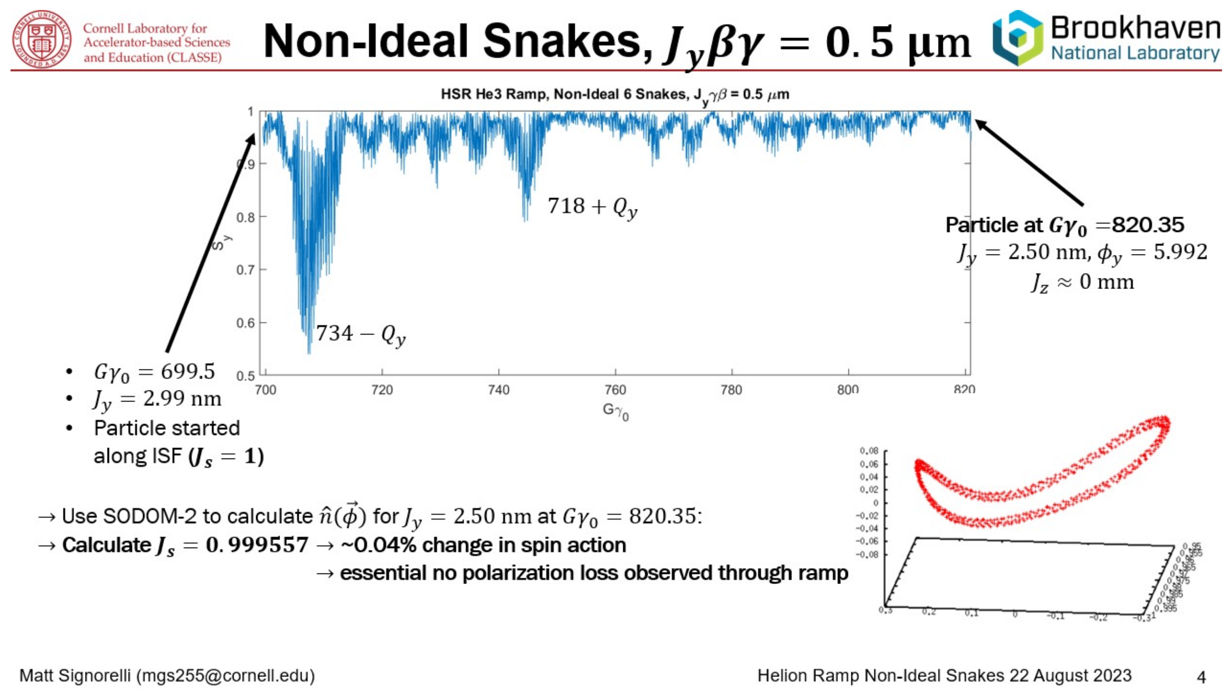
SODOM-2

- "Last summer, major questions about hadron polarization loss during HSR ramp.
- In 1 week, used Bmad's routines to implement an Invariant Spin Field (ISF) calculating program SODOM-2.
- Program easily interfaced with long_term_tracking to do ramping and observe polarization loss.
- **Program still used today for polarization calculations/tracking."**

-- Matt Signorelli, Cornell

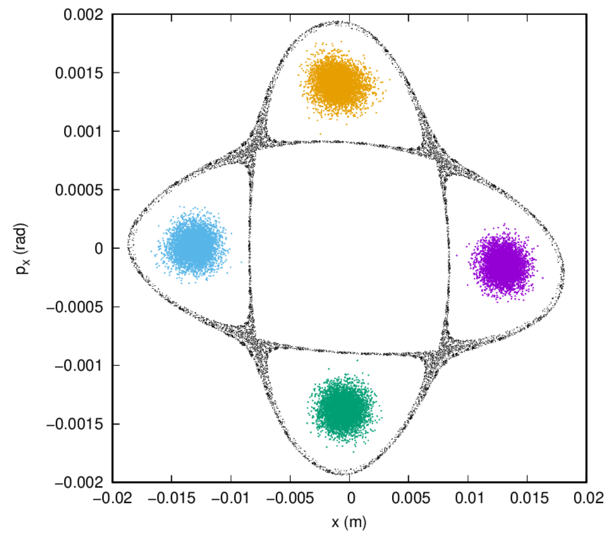


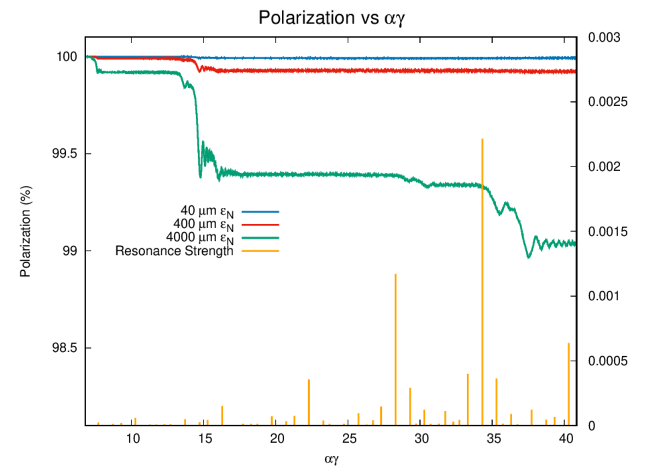
RCS and HSR

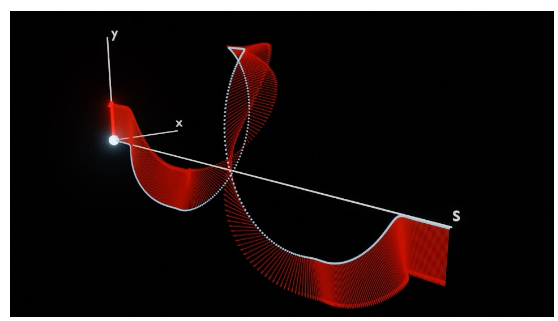
Bmad used for:

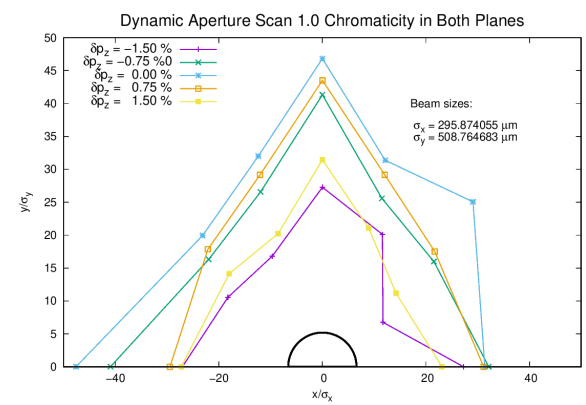
- Transition crossing in the HSR
- RCS linear and non-linear optics
- RCS DA
- RCS magnet error
- RCS damping ring
- design of HSR IR4 optics
- HSR injection optics
- HSR transition optics
- HSR 10 o'clock optics
- HSR emittance growth due to induction septum
- HSR radial shift (circumference lengthening)
- LINAC to RCS transfer line
- RCS to HSR transfer line
- 3D modeling (Bmad + Blender)

-- Henry Lovelace III, BNL









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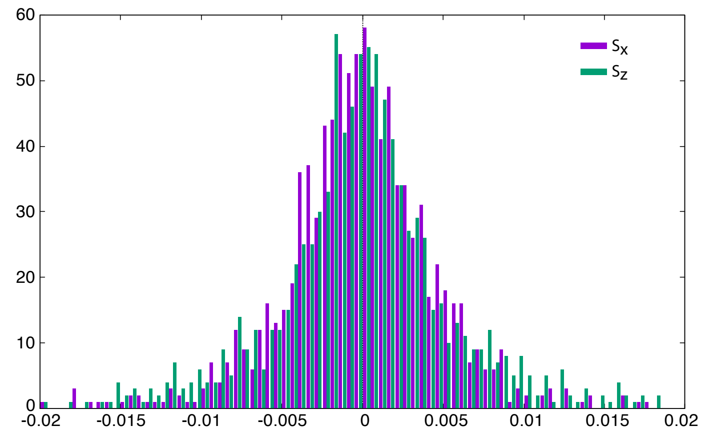
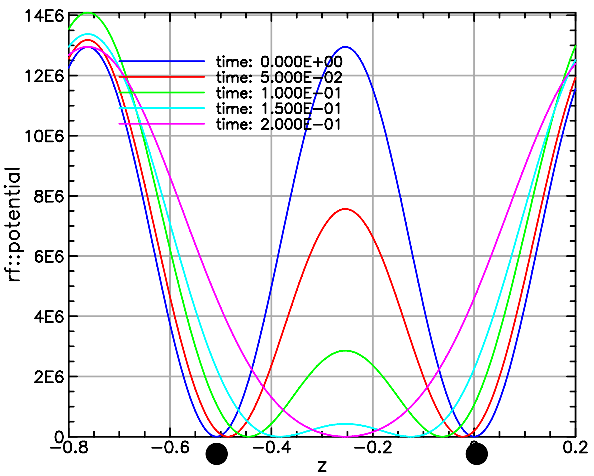
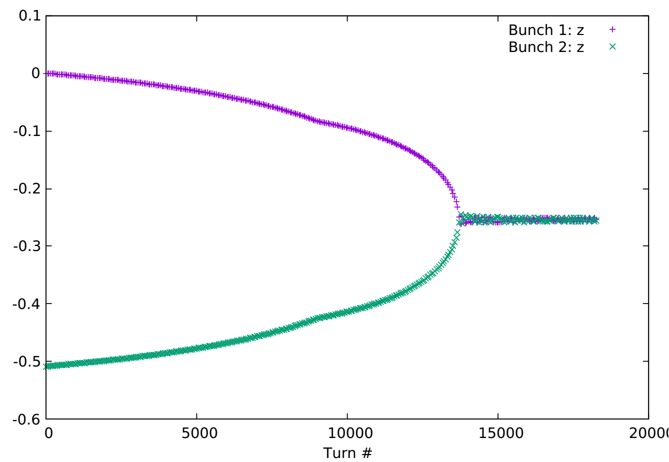
RCS Bunch Merging

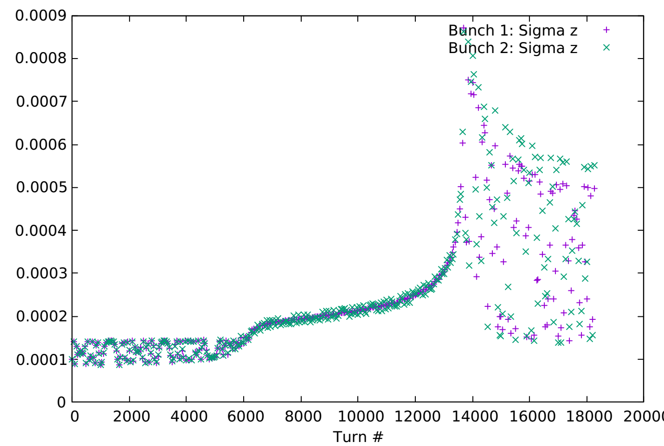
Bunch merging while ramping in the RCS.
Simulation includes spin tracking.

-- David Sagan, Cornell







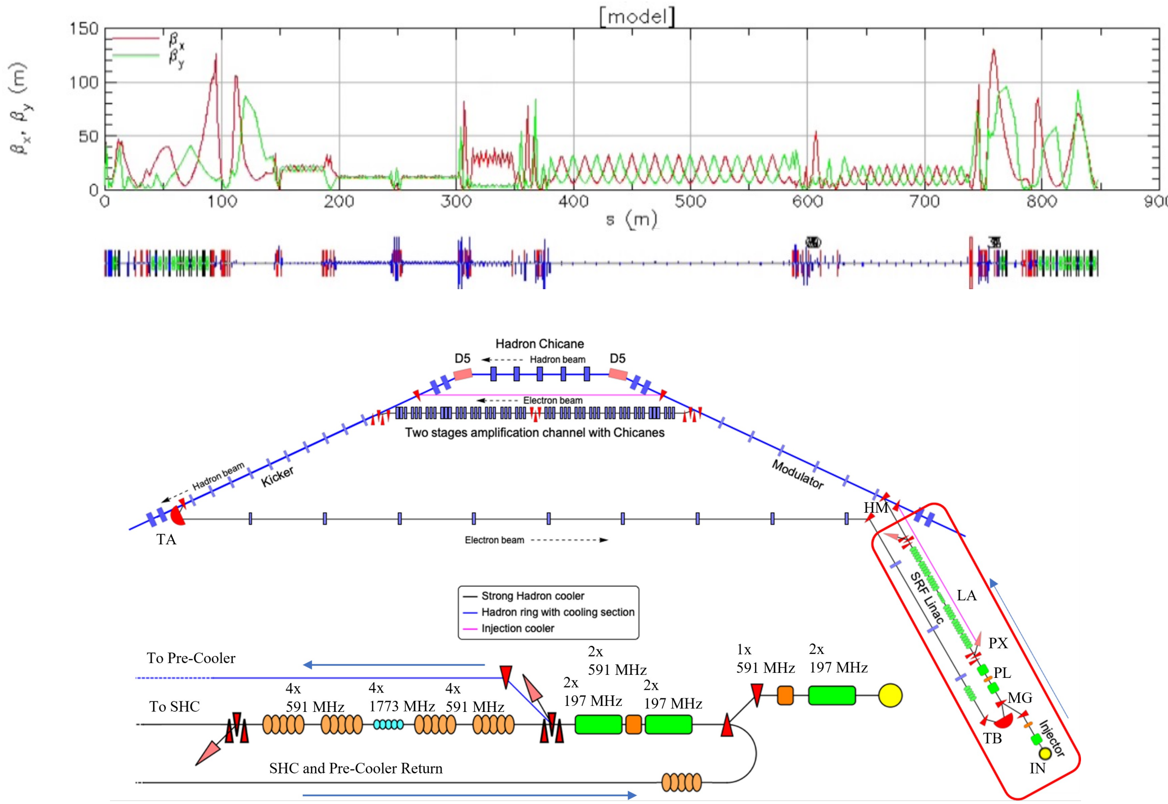


Strong Cooling ERL

Bmad used for:

- Multiple aspects of the ERL, including overall design.
- Space charge simulations of the low energy regions.
- Simulation of the beam breakup (BBU) threshold current.

-- Kirsten Deitrick, JLab



Bmad-Julia

One need for Machine Learning in Operations

Optimizers for different applications

less ← assumed knowledge of machine → more

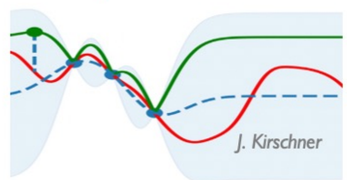
Model-Free Optimization

Observe performance change after a setting adjustment

→ estimate direction or apply heuristics toward improvement

gradient descent
simplex
ES

Model-guided Optimization

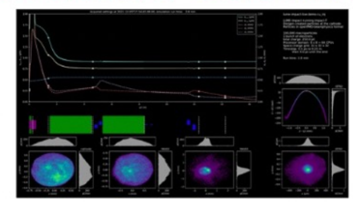


Update a model at each step

→ use model to help select the next point

Bayesian optimization
reinforcement learning

Global Modeling + Feed-forward Corrections



Make fast system model

→ provide initial guess (i.e. warm start) for settings or fast compensation

ML system models +
inverse models

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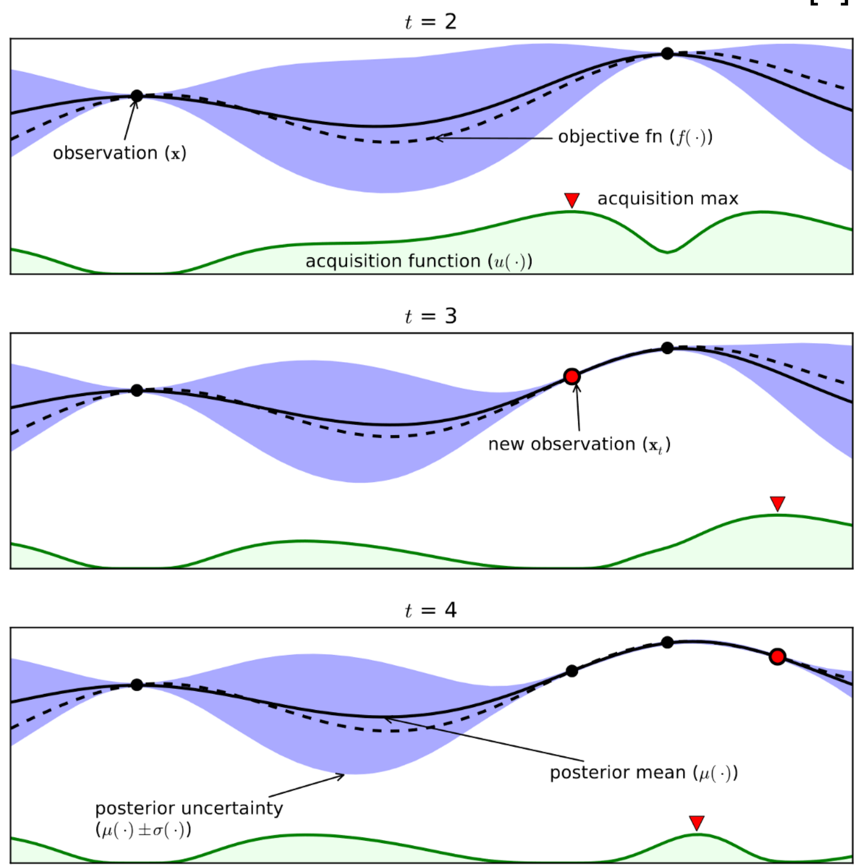
Courtesy Auralee Edelen

Acquisition Function

[2]

- Guide how input space should be explored during optimization
- Combine predicted mean and variance from Gaussian Process model
  - Probability Improvement (PI)
  - Expected Improvement (EI)
  - **Upper Confidence Bound (UCB)**

$$\mathbf{UCB}(\boldsymbol{x}) = \boldsymbol{\mu}(\boldsymbol{x}) + \boldsymbol{\kappa}\boldsymbol{\sigma}(\boldsymbol{x})$$



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Advantages of Bayesian Optimization

Summary of optimization methods

	Nelder-Mead	Gradient descent	Powell / RCDS	L-BFGS	Genetic algorithm	Bayesian optimization
Sample efficiency	Medium	Medium	Medium/high	Medium/high	Low	High
Computational cost of picking the next point	Low/Medium	Low	Low	Low	Medium (e.g. sorting)	High (esp. in high dimensions)
Multi-objective	No (but can use scalarization)	No	No	No	Yes	Yes
Sensitivity to local minima	High (but can use multi-start)	High	High	High	Low	Low (builds a **global** model of f)
Sensitivity to noise	High	High	High (Powell) Low (RCDS)	High	Medium	Low (can model noise itself)

Summary of optimization methods

	Nelder -Mead	Gradient descent	Powell / RCDS	L-BFGS	Genetic algorithm	Bayesian optimization
Requires to compute or estimate derivatives of f	No	Yes	No	Yes	No	No
Evaluations of f *inherently* done in parallel	No	No	No	No	Yes	No
Hyper-parameters	Initial simplex	Step size: α (+momentum: β)	# fit points Noise level	Accuracy of hessian estimate	• Population size • Mutation rate • Cross-over rate • Number of generations	• Kernel function • Kernel length scales, amplitude • Noise level • Acquisition function

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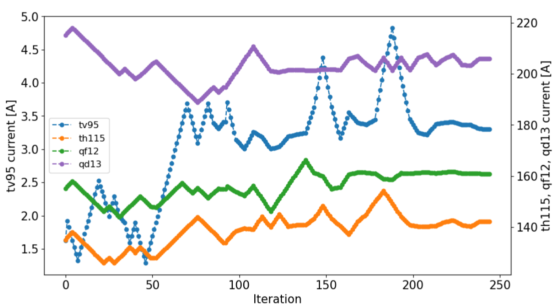
Ex.: Booster transfer optimization by Bayesian Learning

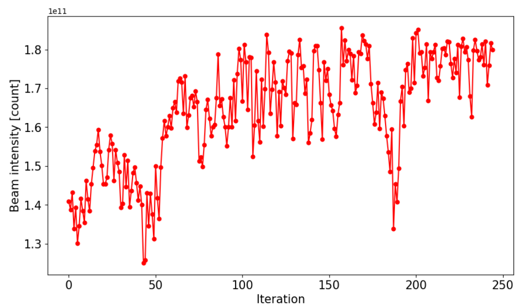
(1) Emittance reduction in L2B and B2A injection and Booster/AGS optics correction and re-bucketing.

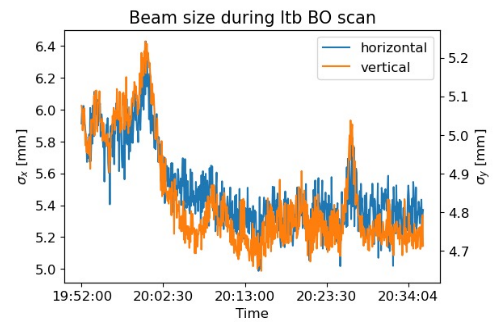
Status:

(a) Detailed, improved models of L2B, B2A, Booster, and AGSs were established with Bmad.

(b) Accelerator studies of L2B injection with Bayesian Learning increases intensity and reduces beam $\sigma_{x/y}$ during accelerator studies in March (Lucy Lin visit).







L2B bend & quad training ➔ Intensity increase ➔ reduces extracted $\sigma_{x/y}$

Future:
- Accel. parameters determined by ML from measured orbit responses (current exp.)
- Modeling of rebucketing in Booster and AGS. (near future beam exp.)
- Modeling of resonance strength correction by skew quadrupoles. (future beam exp.)

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Bmad-Julia: The Future of Machine Learning Focused Accelerator Modeling

Project Objectives:

- Using the experience gained with Bmad, create simulation packages using the Julia Language that has Machine Learning (ML) / Artificial Intelligence (AI) capabilities built in from the ground up.
- Neural networks as element, forward automatic differentiation embedded, e.g., for NN parameter optimization.
- The project will engage the entire accelerator community to promote sustainability and portability of the software. Currently there is participation of people from Cornell, BNL, RadiaSoft, SLAC, ANL, Berkeley Lab, JLab.
- Weekly Wise People Meeting for coordination every Thursday 4pm EST.
- This gives the Bmad-Julia project the potential to revolutionize accelerator simulation program development just as Geant4 has revolutionized the simulation of particle-matter interactions.

Due to Bmad's wide adoption and breadth of capabilities, for the foreseeable future, Bmad-Julia will not be a replacement for Bmad and both will coexist side by side.

Project Status: Started in 2023, DOE funding has been applied for, and open source packages are in development for

- Lattice instantiation and manipulation.
- Truncated Power Series Algebra (Taylor maps, in collaboration with Laurent Deniau)
- Normal form analysis including spin (in collaboration with Etienne Forest)
- Atomic and physical constants.

And much more to do...

Conclusions

Conclusions

- Bmad encompasses a flexible simulation environment with extensive modeling capabilities unmatched by any other code.
- Bmad's modular design means that extending Bmad to encompass new physics requires less time and results in fewer bugs. This is especially important for projects like the EIC where modeling requirements are constantly evolving.
- Bmad has been and remains engaged in many aspects of the EIC design.
- The Bmad-Julia project will greatly facilitate machine learning / AI simulations.
- Furthermore, Bmad-Julia has the potential to revolutionize accelerator simulation program development facilitating the creation of better simulation programs and saving countless hours of development time.

Thanks To

David Rubin
Georg Hoffstaetter
Etienne Forest
Desmond Barber
Jonathan Laster
Mark Palmer
Matt Rendina
Attilio DeFalco
Frank Schmidt
Hans Grote
Martin Berz
Dan Abell
Jacob Asimow

Ivan Bazarov
Moritz Beckmann
Scott Berg
Oleksii Beznosov
Kevin Brown
Joel Brock
Sarah Buchan
Avishek Chatterjee
Jing Yee Chee
Christie Chiu
Joseph Choi
Robert Cope
Jim Crittenden

Laurent Deniau
Bhawin Dhital
Gerry Dugan
Michael Ehrlichman
Jim Ellison
Ken Finkelstein
Mike Forster
Thomas Glassle
Juan Pablo Gonzalez-Aguilera
Sam Grant
Colwyn Gulliford
Eiad Hamwi

Klaus Heinemann
Richard Helms
Lucy Lin
Henry Lovelace III
Chris Mayes
Vasiliy Morozov
Karthik Narayan
Katsunobu Oide
Tia Plautz
Matt Randazzo
Robert Ryne
Michael Saelim
Jim Shanks

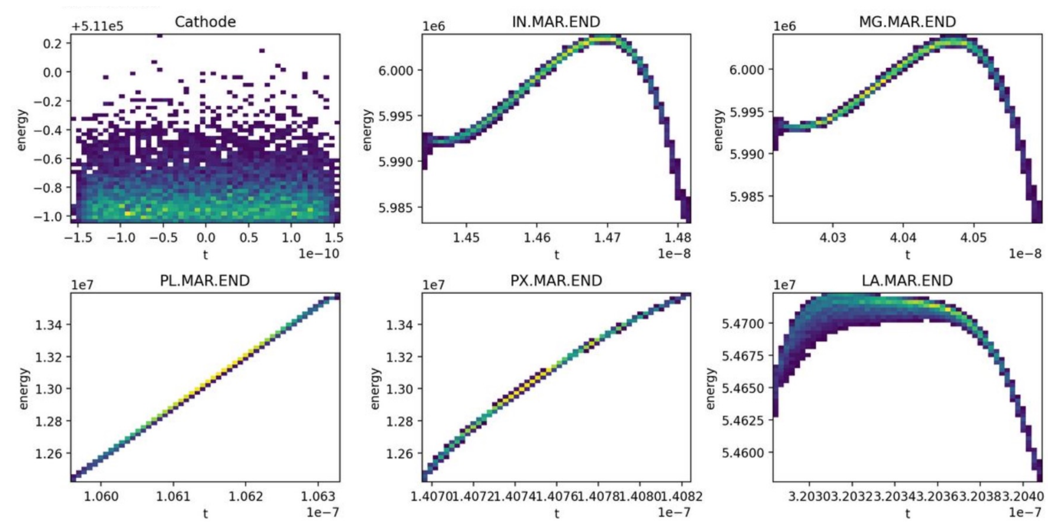
Matthew Signorelli
Hugo Slepicka
Jeff Smith
Jonathan Unger
Jeremy Urban
Ningdong Wang
Suntao Wang
Mark Woodley
Demin Zhou

Thank You

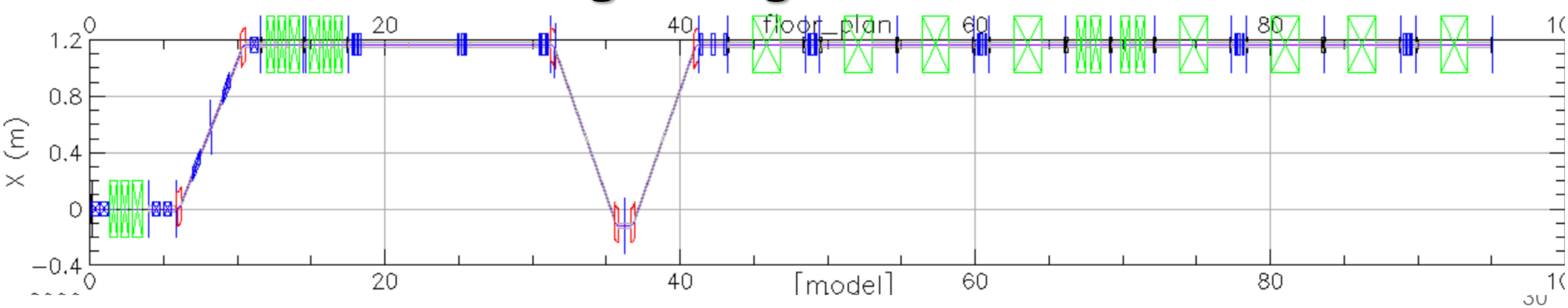
Bmad Applied to the EIC

- Simulation of injector for the EIC SHC cooler ERL using Bmad
- Laser shaping and lattice optimization of the EIC SHC cooler ERL for uniform cooling distribution

  - Ningdong Wang



Simulating from gun to the end of linac



Bmad Applied to the EIC

Bmad is now used for constructing simulation models for the majority of the injector compound for RHIC and future EIC, including the Linac to Booster (LtB) transfer line, Booster ring, Booster to AGS (BtA) transfer line, and the AGS ring. It is used to produce simulation data for beam experiments such as orbit response matrix measurements and quadrupole scans, both as training data for machine learning algorithms, and for development of digital-twins for the accelerators. - Lucy Lin