Simulation for Muon g-2

James Stapleton

Computing Readiness Review

7 November 2016

Physics Needs

- Physics dictates the requirements of our simulation
- Simulation sharpens our understanding of real-world physics
- Some of our needs are **unique**

Major Goals

1) Characterize muon storage/loss at injection and throughout run
2) Develop/test calorimeter analysis
3) Develop/test tracker analysis
4) Exercise offline data analyses workflow
5) Commissioning analyses

Simulation Framework(s)

We must precisely characterize:

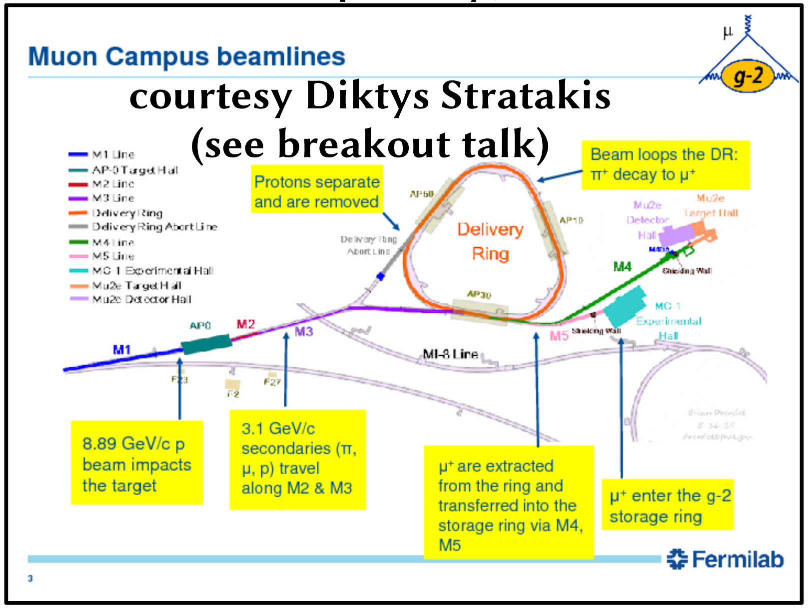
- phase-space of injected muons (strongly affects storage efficiency)
- spin distribution at injection (and correlation with momentum)
- muon distribution in storage region (convoluted with B field to obtain precession frequency)
- time-dependent fields (tuning storage efficiency using kicker/quads)
- material geometries (especially near storage region)
- detector response to our signal+background

Break problem into multiple stages:

- G4Beamline: proton target, beamline propagation, pion decay in booster ring, and muon delivery to MC1
- gm2ringsim: muon injection into ring, fine-tuning of orbital radius and muon phase space, muon decay, and muon/positron signal in detectors
- BMAD: field tuning studies for muon injection (early)

G4Beamline

- End-to-end Geant simulation from proton target to muon delivery to MC1
  - Track beam **(including polarization)** through beam lines and delivery ring
  - Must account for multiple bends, elevation changes, and injection/extraction schemes
- Works with other tools to simulate production on target and beamline optics
- **Critical** to understand **spin-momentum correlation** at storage ring entrance (measurement systematic on precession frequency)
- Also delivery efficiency (normalization)
- Independent of art, gm2ringsim
- Cross-checked with other tools
- Using NERSC resources successfully
- (More details in Diktys' talk)



gm2ringsim

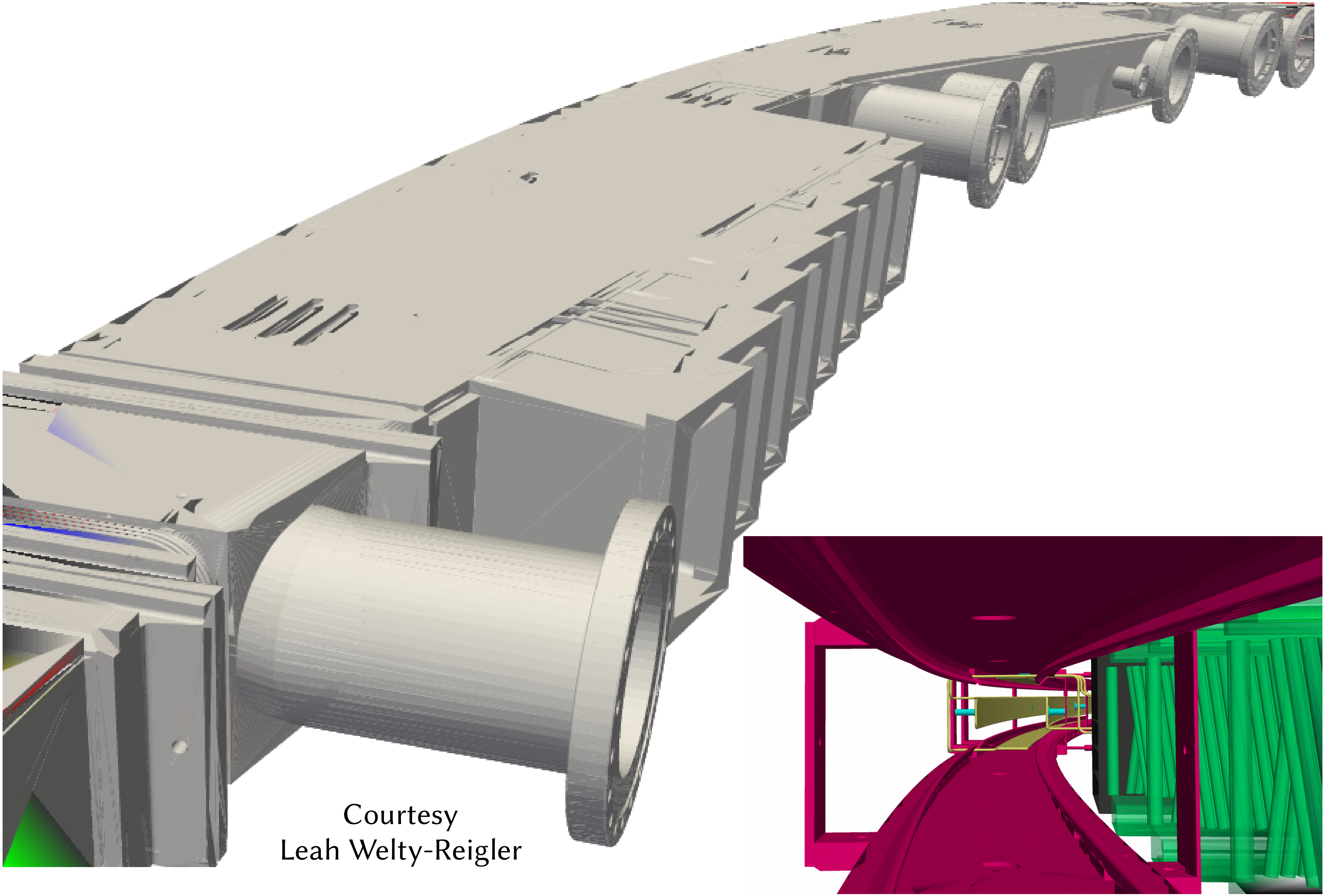
- Geant4 simulation of ring, fields, muon behavior in storage, and signal in our detectors
  - includes realistic material geometry and electromagnetic fields
- Accompanies our art analysis framework
- Under development since ~2013
- Really four separate packages/repositories (for now)
  - artg4: generic Geant4 interface to art
  - gm2geom: describes geometry of our experiment
  - gm2ringsim: Geant4 driver (via artg4) using gm2geom
  - gm2dataproducts: all art records produced by our experiment
- Soon: most packages will likely be merged into a single repository for reasons discussed in Adam's computing overview

gm2ringsim Event Generation

- **Event generation** is simply particle injection using Geant ‘particle guns’
- Muon Guns: high-fidelity, full simulation of muon propagation from some fixed starting point
  - specify phase space and spin
  - shoot muons from various stages (inflector entrance or exit, or at end of G4Beamline)
- Muon Gas Guns: parametrically emulate muon storage, behavior, and decay in ring
  - skip muon propagation to save simulation time (for fast studies of background and other effects)
  - inject muon at decay time
- Particle Bomb: isotropic multi-species source
  - designed to test Geant geometry

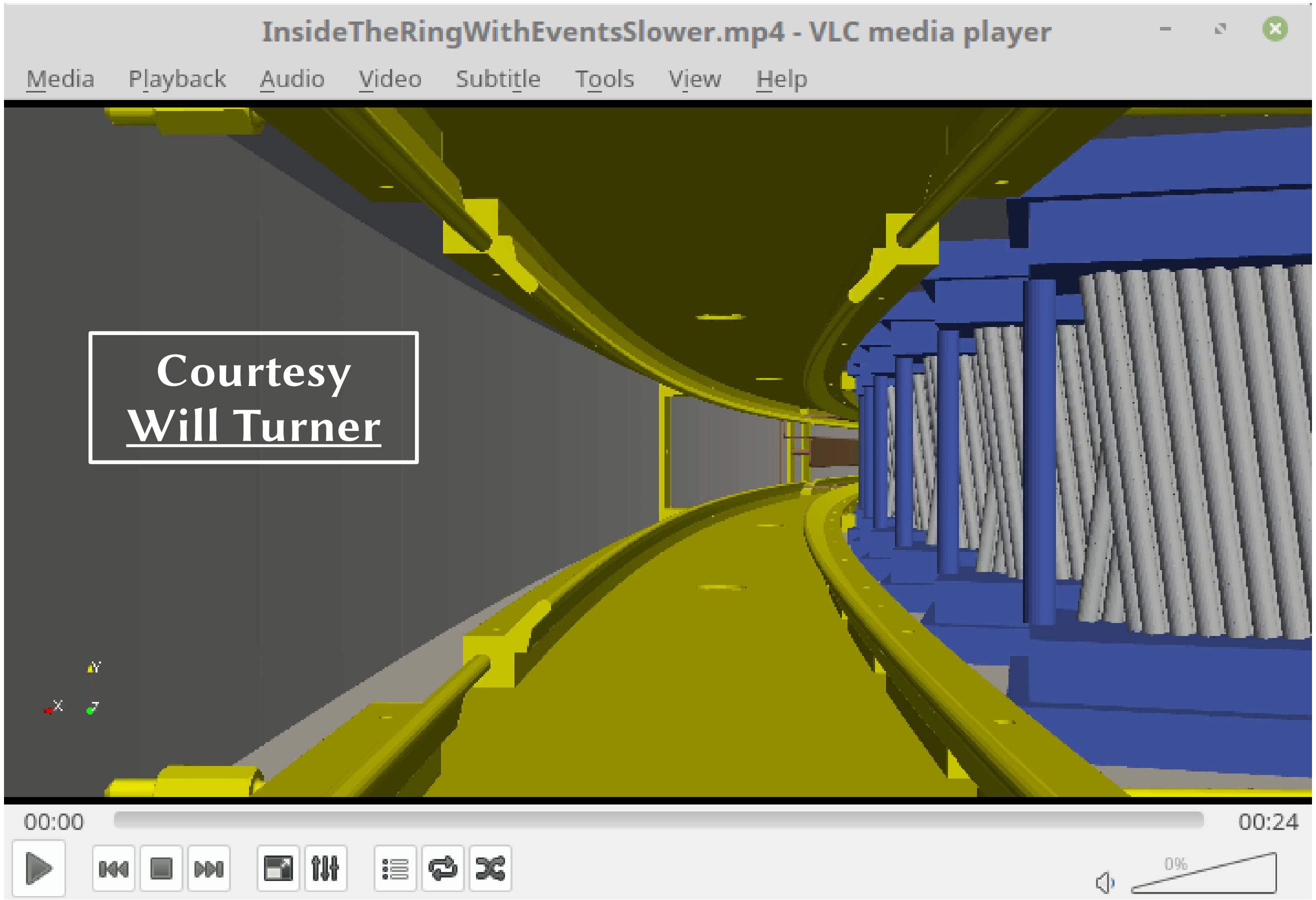
gm2ringsim Geometry

- Unique challenge: we have complex structures **very close to the beam**
  - necessary due to requirements on size, field(s), cooling, and instrumentation
  - this is particularly important for study of muon loss
- Standard approaches (using native Geant volumes or GDML) do not sufficiently describe these structures
- Geometry development has accelerated recently due to Cadmesh
- **Cadmesh** allows us to import native CAD file formats (STL, PLY, others) directly into Geant-manageable geometry
  - this is as close as Geant can get to 'the real thing'
  - does not require "intermediate file format conversion using commercial software"[arXiv:1105.0963]
  - this fixed a **serious roadblock** to our geometry implementation
  - represents a **unique contribution from g-2** to physics simulation methods
- For more details, see Leah's geometry talk



Courtesy
Leah Welty-Reigler

A Brief Tour…


InsideTheRingWithEventsSlower.mp4 - VLC media player
Media
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Courtesy
Will Turner
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gm2ringsim

- The simulation has **already been used for successful studies**, well before its implementation is complete
- These studies regularly influence the experiment's design (hardware **and** software)
- Highlights of a few results:
  - Quadrupole, inflector design studies
  - Calorimeter signal study
  - Tracking/EDM studies
- We have remaining development goals that are **crucial** to our measurement
- Current implementation campaign focuses on these goals

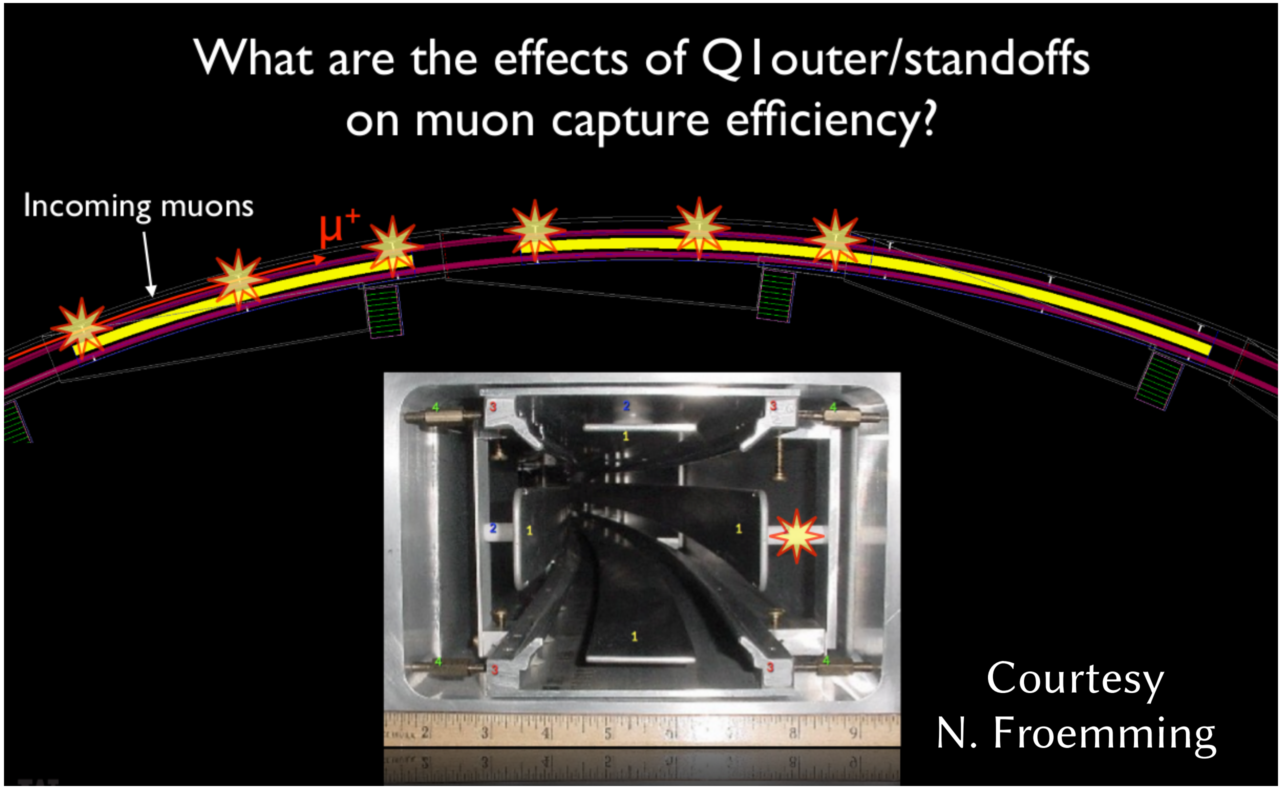
Selected gm2ringsim Studies

Quad Plates and Standoffs

Nathan Froemming 2015

Problem: muons exit inflector and hit quadrupole plates (and the 'standoffs' which support them)

Originally thought to impede beam at level of ~few percent

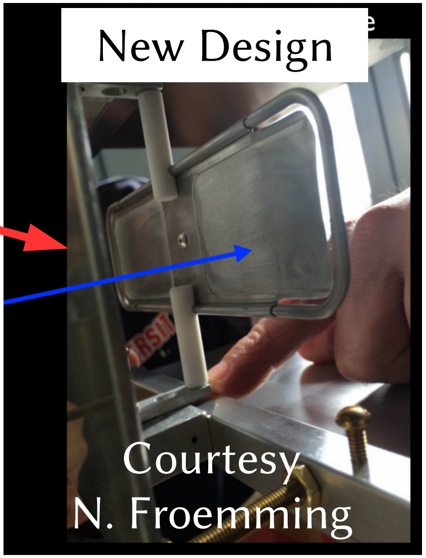


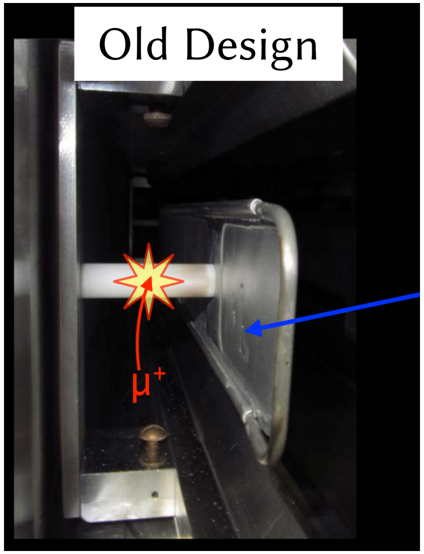
Selected gm2ringsim Studies

Quad Plates and Standoffs

Nathan Froemming 2015

- Study with gm2ringsim tested different standoff design
  - allow unobstructed muon passage behind plate!
- Muon storage efficiency jumped from 2.31% to 2.84%
  - **this is a 23% increase in data**
- Similar problem: beam passes **through** Q1 outer plate
  - thin aluminum plate, but still contributes to loss
- Same study also tested materials:
  - build plate from lower-*Z* material, cover in aluminum
  - boosts 2.84% storage efficiency to 3.34%
- **45% data increase in total**
- **<u>Simulation results have informed hardware design</u>**
- Simulation materials have been updated as well



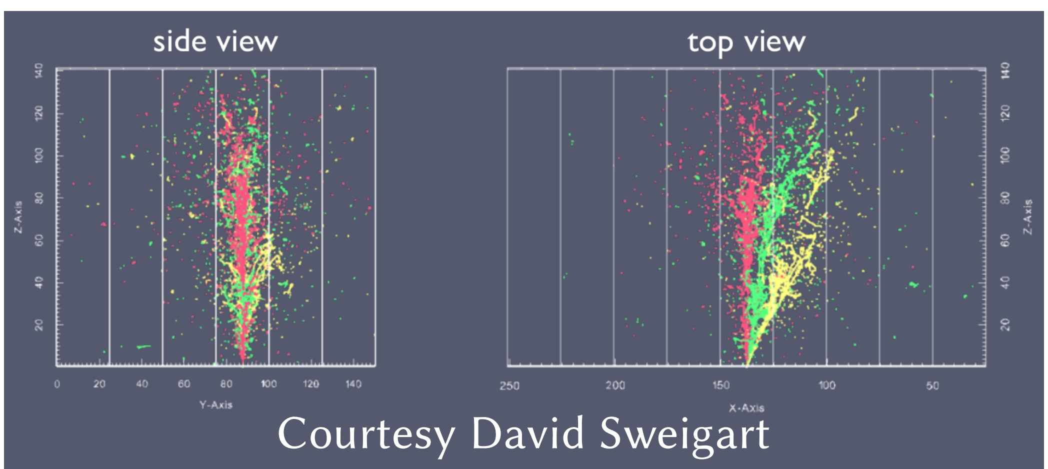


Selected gm2ringsim Studies

Calorimeter Cluster Position

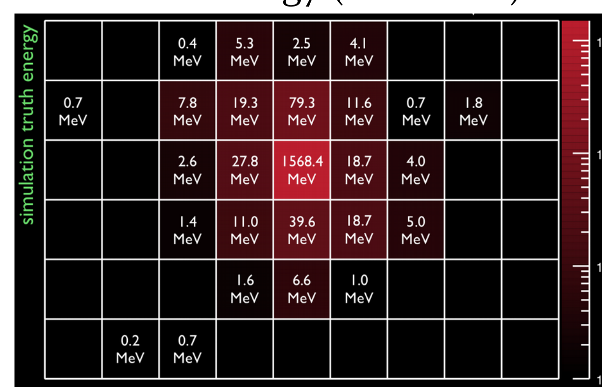
David Sweigart 2016

- Calorimeter tested with electron beam at SLAC
- Before test run, David surveyed methods reconstructing **position** and **angle** of beam from crystal data
- This was critically important to **fast-turnaround analysis** in test run
- Required **Geant simulation of EM cascade** in crystals
- Method with best performance worked **out of the box** for real data



Courtesy David Sweigart

truth energy (front view)



Courtesy David Sweigart

Physics Needs

Major Goals

1) Characterize muon storage/loss at injection and throughout run
2) Develop/test calorimeter analysis
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4) Exercise offline data analyses path
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Muon Loss and Storage Efficiency

- Muon beam momentum spread is **much** wider than the maximum 'momentum acceptance' of our storage ring
- We are forced to accept **~95% muon loss** in injection and first turn in storage
  - 94% vs 97% would be a **potential factor of two in useful statistics**
- Beam injection: study storage efficiency as a function of:
  - kicker pulse strength and timing
  - quadrupole scraping to 'clean up' muon phase space
- 'Lost Muon' signal
  - use simulation to relate loss to a measurable signal (don't just trust simulated storage efficiency)
  - need a high-fidelity signal as a proxy for measurement of storage efficiency
  - muon coincidence in consecutive calorimeters (and background for this signal)

Muon Loss and Storage Efficiency

Status

- Preliminary studies of kicker timing have been done in gm2ringsim
  - ‘fakes’ propagation through inflector (injects muons at inflector exit)
  - uses 2D field map (swept through ring azimuth to generate 3D field)
- Studies of materials (quad plates, collimators) mostly finished
- Lost muon signal: studies of multi-calorimeter coincidence have started

Plans

- Finish gm2ringsim studies, including
  - propagation from ‘upstream’ through inflector
  - implement 3D kicker/quadrupole fields
  - test kicker timing and various quad scraping programs
  - finish calorimeter coincidence study

Develop/Test Calorimeter Reconstruction

- Energy/time/angular resolution
- Develop and test
  - pulse fitting algorithms in crystals
  - cluster-finding algorithms (combining crystal pulses)
  - identification of ‘pile-up’ (coincident positron hits) and background
- Test performance of these algorithms using SLAC data
  - tested calorimeter prototype in SLAC’s electron beam (June 2016)
  - this test **exercised software** as well
  - analysis implemented **within art** using gm2ringsim (with flexibility of artg4)
  - compare SLAC data to calorimeter simulation

Develop/Test Calorimeter Reconstruction

Status

- ongoing work characterizes efficiencies of pulse fitting and clustering
  - pulse-fitting is robust
  - temporal clustering is working well, spatial clustering needs more work

Plans

- finish main fitting/clustering algorithms
- work on 'pile-up' identification algorithms
- test performance **with background** from secondaries
- experiment with alternative/independent algorithms
  - maybe even machine learning for clustering

Develop/Test Tracker Reconstruction

- We need algorithms for track-fitting straw signals
  - muon decay position is unknown (so it can't be used for fitting algorithms)
- Use tracks to reconstruct muon spatial distribution in storage region
  - method will rely on simulated spatial distribution as we **cannot directly measure** muon distribution
  - target: extract this distribution shape with accuracy to sub-mm level
- Understand track-finding efficiency in relation to
  - **non-uniform magnetic field in tracker region**
  - particle energy, and chosen signal threshold
  - muon decay location, number of planes hit, vertical pitch
  - background from lost muons and low-energy secondaries

Develop/Test Tracker Reconstruction

Status

- currently characterizing signal generated in straws
- track-fitting algorithms under development

Plans

- finalize generated signal in straws (ongoing)
- finish developing/testing tracking algorithms (ongoing)
- reconstruction of injected muon beam is waiting on track-fitting (waiting on above)
- See Tammy's talk for more information

Exercise Offline Data Handling

- Generate a **large simulated sample**
- Use this sample to:
  - ensure an analysis path is implemented by Day 1
  - test full-scale handling of our data
- Analyses not mentioned above: spin precession, fast rotation, pitch correction, betatron oscillations
- Status: early production of large data sets has enabled high-statistics preliminary analysis
- Plans:
  - production team: large, high-quality muon simulations
    - full muon propagation, spin evolution
    - generate and digitize signals for ‘mock data’
  - use ‘mock data’ to develop art analyzer modules
    - pitch correction, spin precession needed by turn-on
    - fast rotation and betatron oscillation studies soon afterward

Commissioning Analyses

- Troubleshooting/diagnostic signals (how can we directly test the performance of the ring on Day 1?)
  - Fiber Harps and Inflector Beam Monitoring System (IBMS) are critical diagnostics
  - scan field timing parameters, compare storage efficiency to simulation
- Characterize effects from misalignments of our fields
- Status:
  - fiber harp analyses beginning now
  - IBMS hardware still under construction
- Plans:
  - IBMS needs g2ringsim for design decisions **and** analysis modules for Day 1

gm2ringsim Tasks Timeline

	Task	Status	Deadline
Implementation	Material geometry	90%	Jan 2017
	Fields	80%	Jan 2017
	Injection/Beam dyamics	60%	Jan 2017
	Detectors signal(s)	80%	Jan 2017
Studies	Muon storage/loss	40%	Mar 2017
	Calo. algorithms	90%	Mar 2017
	Tracker algorithms	30%	Mar 2017
	Commissioning studies	10%	June 2017
Testing	Offline analysis workflow	70%	Ongoing
	gm2ringsim optimization	30%	Jan 2017

~15 people working on this

Implementation Timeline

	Task	Status	Deadline
Material Geometries	Vacuum chambers	100%	Feb 2017
	Injection line	20%	Jan 2017
	Quadrupole plates	95%	Jan 2017
	Kicker plates	80%	Jan 2017
	Trackers	95%	Jan 2017
	Calorimeters	95%	Jan 2017
Fields	Storage field (and fringe)	90%	Jan 2017
	Quad fields	80%	Jan 2017
	Kicker fields	70%	Dec 2016
	Unification	95%	Nov 2016
	Misalignments	0%	Mar 2017

~10 people working on this

Implementation Timeline

	Task	Status	Deadline
Injection and Beam dynamics	Muon Gas Gun	100%	Feb 2017
	Inflector Gun	100%	Nov 2016
	Kicker field timing/scaling	50%	Jan 2017
	Quad field scraping	20%	Jan 2017
	Fiber harps	10%	Jan 2017
	IBMS	10%	Jan 2017
	Virtual ring monitors	30%	Nov 2016
	Larger G4Beamline sample	100%	Dec 2016
Detector signal	Calorimeters	50%	Feb 2017
	Trackers	40%	Feb 2017
	Fiber Harps	10%	Mar 2017

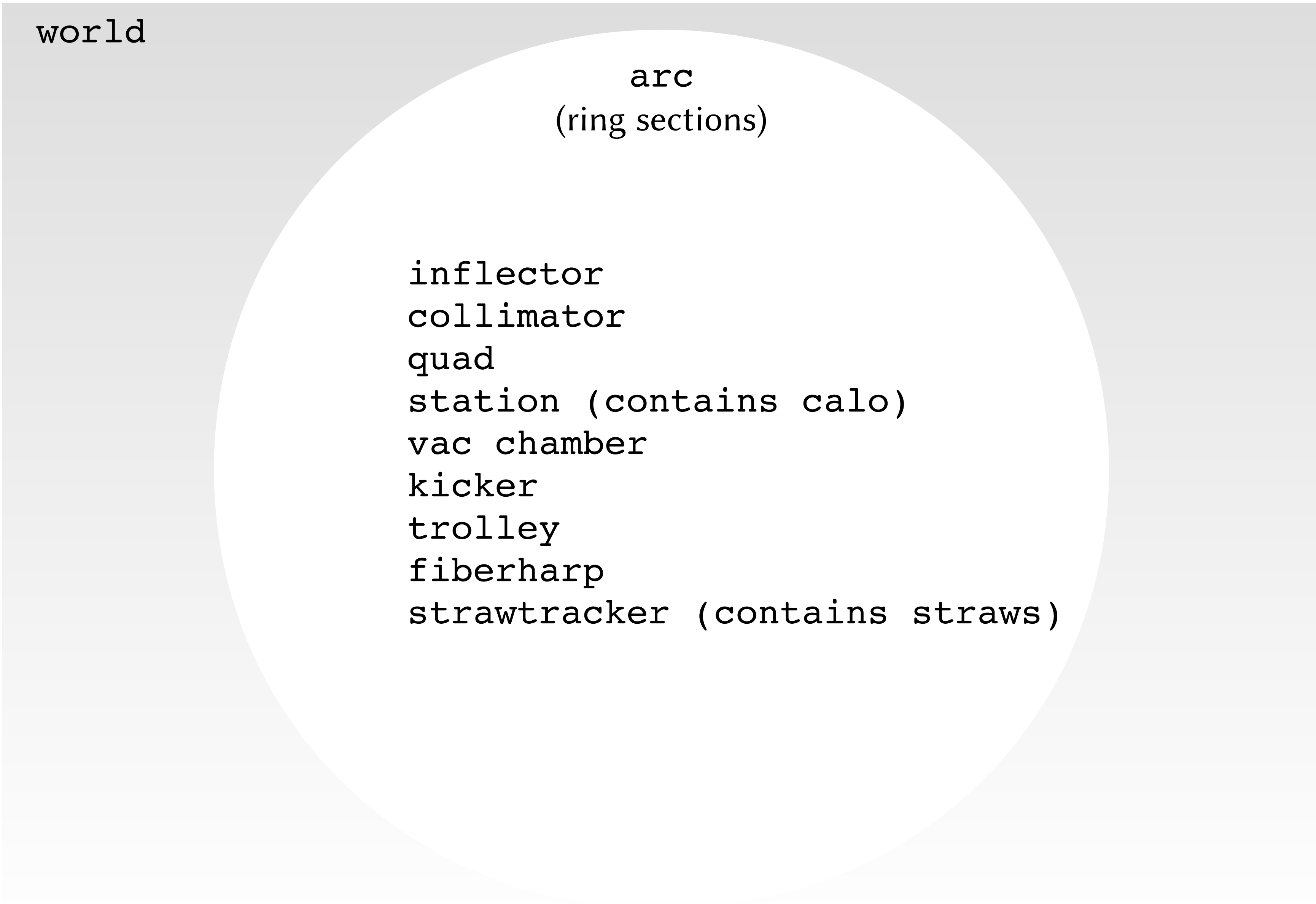
~10 people working on this

Conclusion

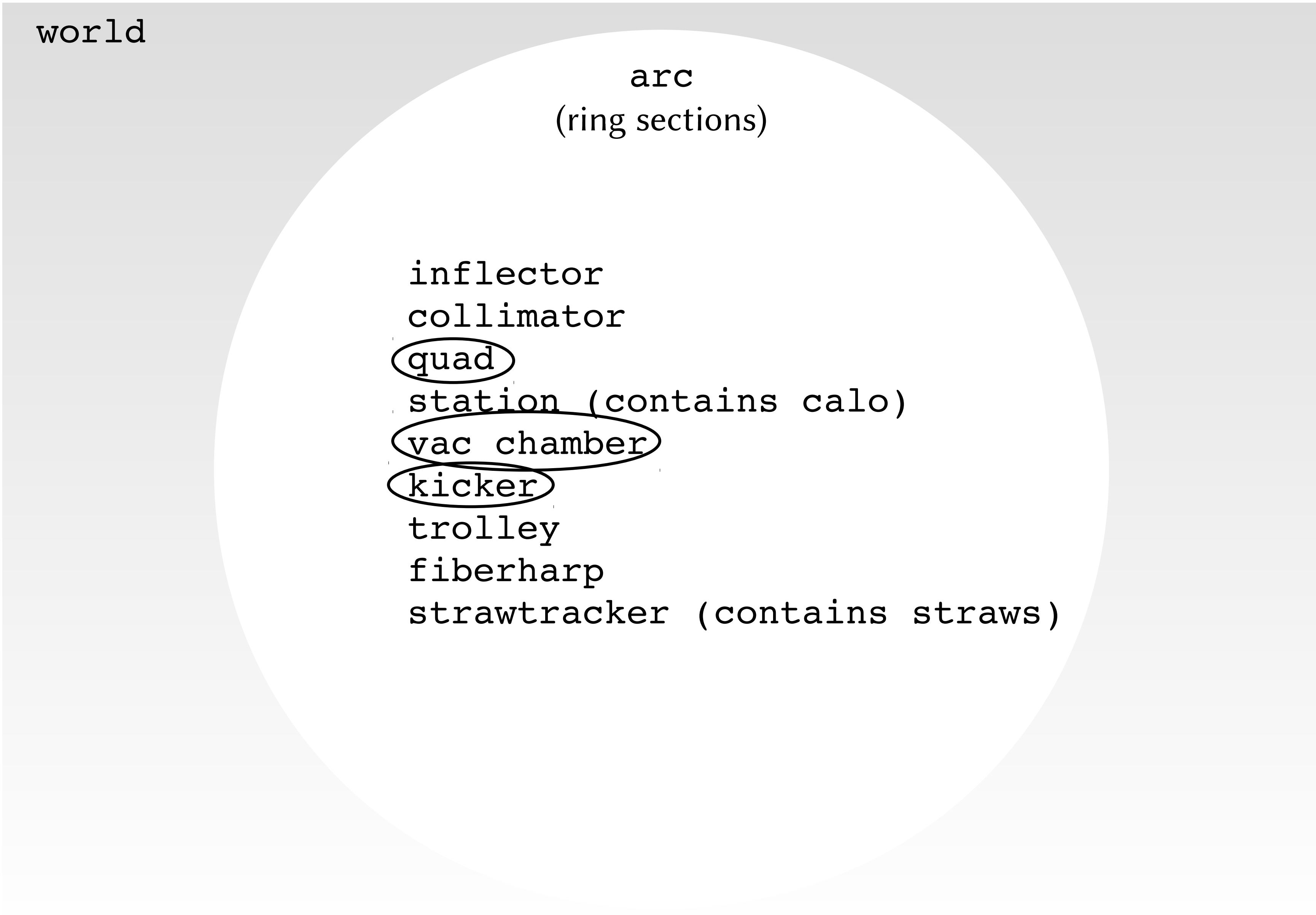
- Simulations have **already been critical** for understanding urgent design and operational issues
  - complementary end-to-end checks (from proton target to detector signal)
  - G4Beamline: dedicated, high-fidelity sim for generation of muon beam
  - gm2ringsim: detailed muon interactions with materials, fields, and detectors in storage ring
- gm2ringsim is currently under heavy development
  - see commit history from Adam's talk
  - analysis and physics goals drive current implementation efforts
  - we have a structured task list
  - our timeline is acheivable

BACKUP MATERIAL

Geant Geometry Heirarchy



EM Fields and Geant Geometry (Old Scheme)



Unified EM Fields

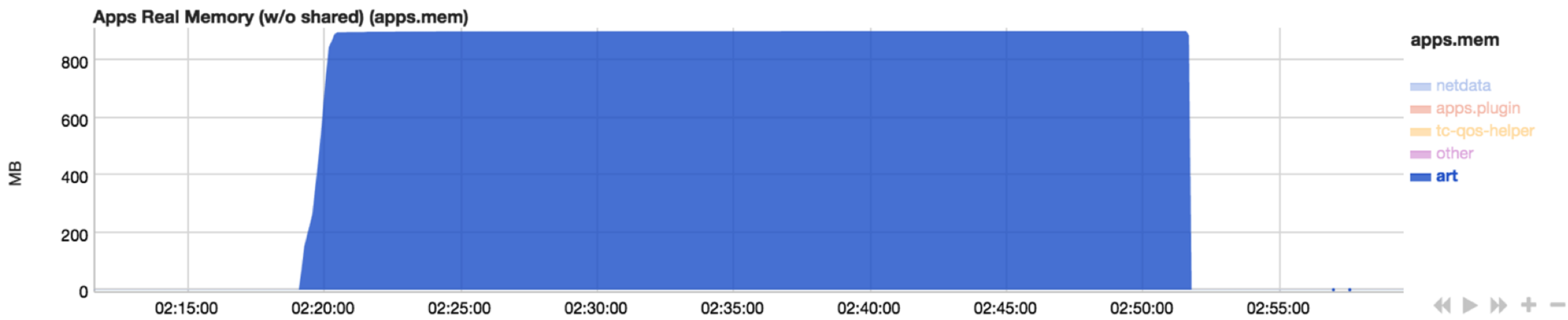
world

arc
(ring sections)

inflector
collimator
quad
station (contains calo)
vac chamber
kicker
trolley
fiberharp
strawtracker (contains straws)

mem

Real memory (RAM) used by applications. This does not include shared memory.



Courtesy Adam Lyon

Modeling: End to End Simulations

Muon g-2

- **G4Beamline**: (BNL)
  - Protons on target
  - Pion production (**MARS**) and capture
  - Muon decay, capture and spin transport
  - All beamlines, “n” turns around DR, beam to ring
- **BMAD** (Cornell)
  - Very fast; well tested; using to guide strategies
  - Lattice-minded code with single particle tracking; apertures; fields;
  - Virtual planes for imaging
- **G4Geant** / **ART** (UW)
  - Relative slow; high fidelity with all physics processes included
  - Complete* geometry and materials; quad/kicker fields and plates; time-dependence; tracking; spin dynamics; decays; detector responses; slow
  - Virtual planes for imaging

*An ongoing challenge with old blueprints and new designs

David Hertzog, Storage Ring Review, May 2015

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Subgoals

<u>Major analysis goals above require:</u>

- **accurate geometry** for all components near storage region, including vacuum chamber and detectors
- **high-quality interactive visualization capabilities** showing hits on ring components and detectors
- **static field(s):** main dipole field and its fringe field outside of storage region
- **time-varying fields** in beam kickers and focusing/scraping quadrupoles
- **Muon Gas Gun** includes fast rotation, CBO, and spin orientation
- can produce **realistic calo crystal pulses** with appropriate statistical smearing and proper energy sharing among crystals
- produce primary and secondary **tracker hits** (background)
- produce **fiber harp and IBMS hits** for beam injection studies
- **verification package:** standard set of physics/statistics checks (see Renee's talk)
- **standardized art records** from simulation

Subgoals I: Geometry

- Geometry must be implemented accurately to simulate muon behavior inside and outside the ideal storage region
- Muons can collide with any components near beam storage region (inflector, quad/kicker plates and standoffs, trolley rails, vacuum chamber)
- Muon trajectories can be affected by calorimeters, trackers, and their housings and accessories
- Proper positioning is important for accurate simulation of signal from tracker straws, Inflector Beam Monitoring System (IBMS), and fiber harps
- Fiber harps with **and** without mass
- Interactive, high-quality visualization capabilities showing detector geometry and hits (artvtk is neat)

Subgoals II: Fields

- static fields:
  - main dipole field and its fringe field outside of storage region
  - our detectors are located within this highly non-uniform fringe field, and it will affect their performance
- time-varying fields:
  - kicker fields tunable to ~10 nanoseconds (for beam injection studies)
  - implement quadrupole scraping (for beam injection studies)
  - specific checks on Geant's handling of quickly-varying fields
    - our experiment will test this much more than most experiments

Subgoals III: Beam Dynamics

- Muon Gas Gun includes fast rotation, CBO, and spin orientation
  - this is mostly verified by Tom Studdard's pass at pitch correction analysis
- Muon Injection Guns (currently under development) exhibit betatron oscillations and fast rotation automatically

Subgoals IV: Detectors

- calorimeters can produce pulses with appropriate statistical smearing and proper energy sharing among crystals:
  - this depends on accurate geometry as well as implementation of materials and EM processes in these materials
  - find something about most recent progress (Kim, Aaron)
- trackers can produce both primary hits and secondary hits (background)
  - Tammy has some work on this?
- fiber harps and IBMS produce hits for beam injection studies

Subgoals V: Verification and Checks

- **verification package:** standard set of physics/statistics checks
- **visualization tools**:
  - Paraview (via heprep-to-vtk conversion plugin)
  - artvtk: write out VTK geometry natively for each detector and art data product

SiPM Gain Response

- SiPMs have nonlinear gain which depends on history
- Our total signal tracks exponential muon decay distribution
- **Therefore, nonlinear gain is driven by a signal which changes by orders of magnitude over a fill**
  - Geant will **NOT** simulate SiPM gain from physics
- Current studies model SiPM gain analytically, and test this model given intensity and time distribution of incident photo-electrons
  - gm2ringsim can **simulate these intensities and time distributions**, and their **relation to deposited energy**
- These inputs will allow studies to optimize corrections for SiPM gain
- Status: not started
- Plans: results from gm2ringsim early enough to facilitate gain studies well before arrival of muons

[include somewhere II]

- ArtG4 makes the simulation extremely flexible and this has been a big success (e.g. used for SLAC and tracker test beams). [we are the only experiment using ArtG4)
- things unique to g-2:
  - GDML cannot satisfy our geometry construction requirements. (We are one of the only experiments not using GDML - need to explain why)
  - We have complicated geometry and that complication matters - using CadMesh to mitigate
  - We have complicated changing magnetic fields
- We can visually verify our geometry with ParaView (of course this isn't the only way we verify).
- Spin tracking (have found bugs in Geant that have been fixed)

[include somewhere III]

- We have flexible and precise particle guns
- We shoot single muons; need to aggregate into fills with art later
- We have digitization for SiPMs and straws
- We have a verification package
- Time estimates for running
- We have done optimization studies (get info from Adam)

Selected gm2ringsim Studies

Tracking and/or EDM Studies

plot(s)

a couple of general points…