On the possible construction of a Mu2e calibration linac built around a spare Project-X or ILC cryomodule

George Gollin[a]
Department of Physics
University of Illinois at Urbana-Champaign
1110 West Green Street, Urbana, IL 61801

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Introduction

One of the challenges awaiting the Mu2e collaboration will be the determination and monitoring of the spectrometer's resolution and energy scale near the electron spectrum endpoint. An ideal calibration technique would permit the collaboration to gauge the precision, absolute energy scale, and level of systematic uncertainties associated with the spectrometer during the time that the experiment is live, recording physics data for the $\mu^- N \to e^- N$ search. Such a calibration system might be realizable through a reconfiguration of the Mu2e calorimeter in combination with the installation of a suitable electron linac. The linac could be built from a spare Project-X (or ILC) cryomodule, and would inject electrons into the *downstream end* of the Mu2e detector.

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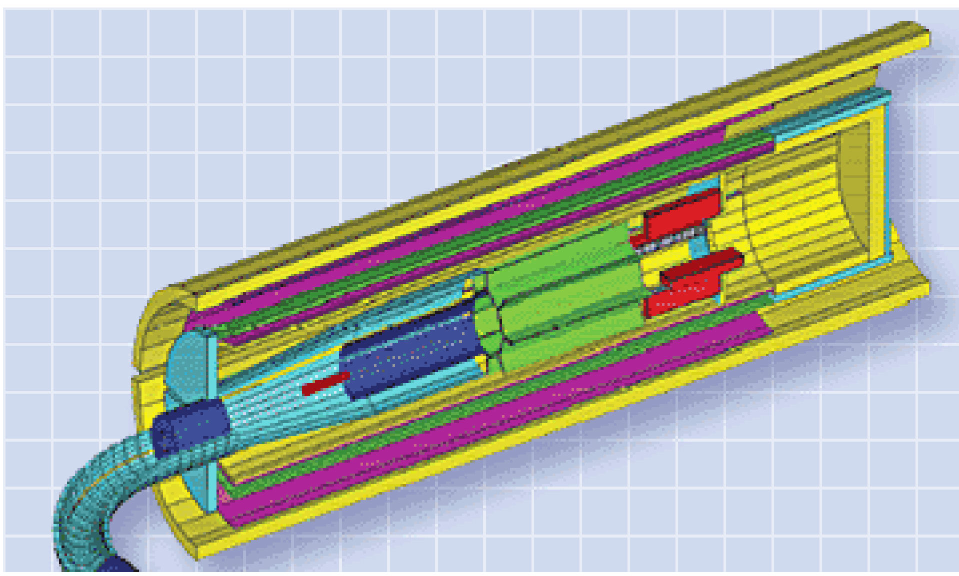
[a] g-gollin@illinois.edu, +1 (217) 333-4451.

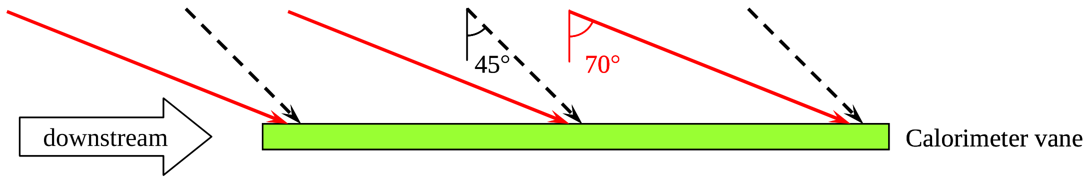
An alternative calorimeter configuration

The design of the Mu2e detector exploits the limited volume of phase space occupied by signal electrons of interest, namely those with momenta in the vicinity of 105 MeV/c. The spectrometer's axial magnetic field confines electrons that leave the stopping target with energies substantially below 105 MeV, preventing them from travelling to sufficiently large radii that they pass through the tracking chamber. Descriptions of the detector in presentations by members of the collaboration generally show it to be similar in overall design to the MECO detector,[1] with an eight-fold axial symmetry to the (octagonal) tracking chamber and a four-fold axial symmetry to the electromagnetic calorimeter. The calorimeter is organized as four vanes of lead tungstanate crystals, oriented parallel to the detector's long axis. An electron will follow a helical trajectory through the tracker, turning in a clockwise sense when viewed from upstream. Typical "pitch angles" for electrons are likely to be[2] in the range 45° - 70° so that electrons will enter a calorimeter vane at a relatively large angle of incidence to the face of the vane.



MECO detector.[3]

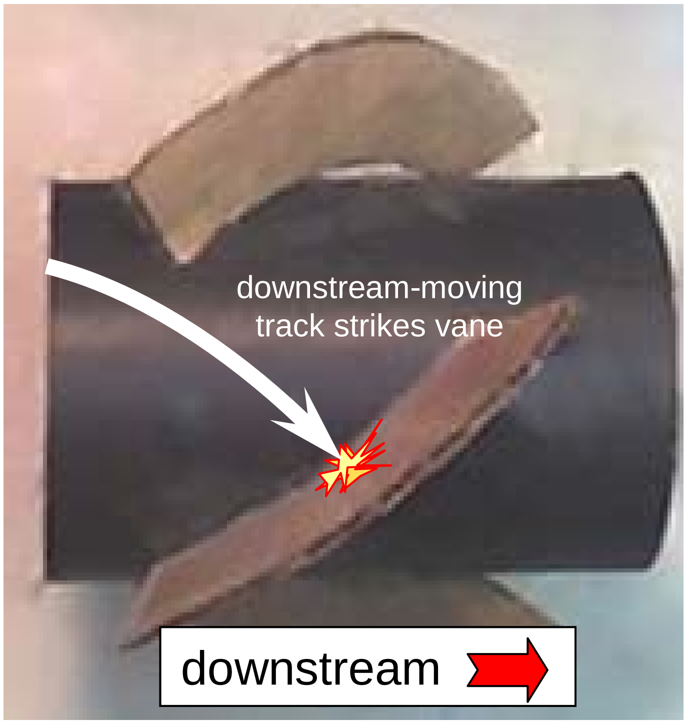
[1] See, for example, W. Molzon, *The MECO Experiment to Search for* $\mu^- N \rightarrow e^- N$ *with* 10^{-17} *Sensitivity*, Nuclear Physics B, **111**, 188, 2002.
[2] Bob Bernstein, private communication.
[3] http://www.bnl.gov/rsvp/images/MECO-w2.gif



Electron tracks striking a calorimeter vane.

The current Mu2e detector layout is “charge symmetric”: the geometric acceptance for a positive 105 MeV/c particle leaving a target foil should be about the same as for a negative particle of the same momentum. But we know the signal of interest will consist entirely of negative electrons, and it is not clear that this charge symmetry affords Mu2e any advantages in sensitivity or precision.

It is interesting to consider a different calorimeter geometry in which the vanes “wrap around” an imaginary cylinder that is coaxial with the tracking detector, much the same way as threads wrap around the barrel of a screw. This would allow incident electrons to strike the calorimeter vanes more squarely. A cardboard mockup of a screw-sense calorimeter is shown in the following photograph. The vanes are represented by the curved corrugated cardboard pieces. (The black cylinder is just a form to which I have mounted the cardboard “vanes” and does not represent part of the Mu2e detector.) The arrow represents the helical path of an electron moving in a generally downstream direction which strikes a vane.



Cardboard calorimeter mockup, with an electron trajectory superposed.

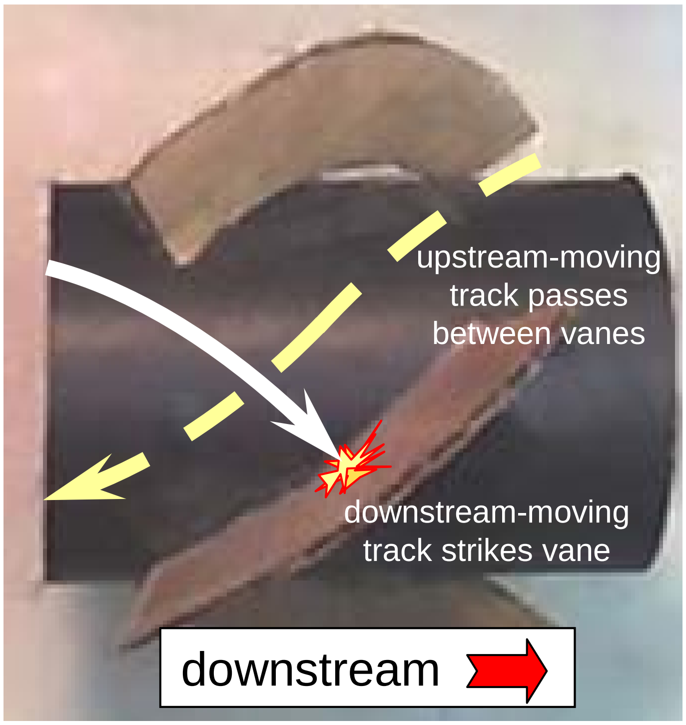
It might be the case that the calorimeter could be built from fewer crystals, reducing the cost of the device while keeping the acceptance from declining. This is a detailed question to be answered through Monte Carlo simulation.

Downstream injection of calibration electrons

Any electron traveling along a path that is not parallel to the spectrometer's solenoidal field will follow a helical trajectory that turns in a clockwise sense when viewed from upstream. It does not matter whether the overall movement of the electron is downstream, as is the case for signal electrons from the stopping target, or upstream, as might be the case for calibration electrons injected in this direction.

Calorimeter vane reconfiguration

If the Mu2e calorimeter is reconfigured with screw-sense vanes, an electron moving through the calorimeter in the upstream direction can be aimed so that it threads its way between vanes without striking the calorimeter. This is illustrated in the next photograph, in which a solid arrow represents the path of a downstream-moving electron, while a dashed arrow represents the trajectory of an upstream-moving electron.

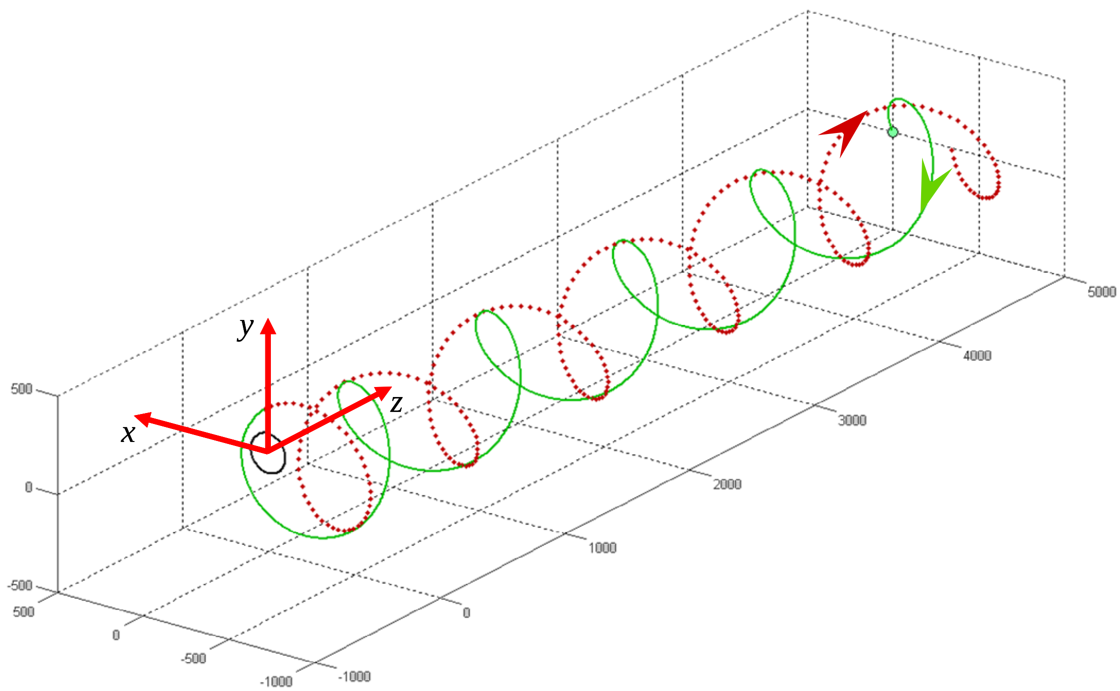


Downstream-moving (solid) and upstream-moving (dashed) electron trajectories. Note how the dashed trajectory threads its way between calorimeter vanes without interference while the solid trajectory strikes a calorimeter vane.

With this calorimeter reconfiguration, an electron could be injected into the detector volume through a shielded channel in the downstream end of the spectrometer vacuum. The electron would follow a helical path that would miss the calorimeter vanes, intersect various layers in the straw tube tracker, and continue towards the stopping target. The inhomogeneous field near the stopping target would reflect the electron, driving it in a downstream direction. Still turning in a clockwise sense but now moving downstream, the electron would again pass through the tracker, but this time would strike a calorimeter vane, producing a shower.

Trajectory of a calibration electron

The path of one electron in a crude representation of the Mu2e magnetic field is shown in the next figure. In the diagram, an electron enters with momentum 105 MeV/c at the point $(x, y, z) = (0, 0, 5000\text{ mm})$ that is marked with a small filled circle. The electron's initial direction of travel is in the y-z plane, tipped up from the negative z direction by 60°. The upstream-moving portion of the electron's trajectory is shown with a solid line; I assume the field downstream of $z = 500$ mm is constant, with strength 1 Tesla. Upstream of $z = 500$ mm the magnetic field pinches down, forming the end of a magnetic bottle so that the electron is reflected. The downstream-moving portion of the electron's path is shown as a dotted line.

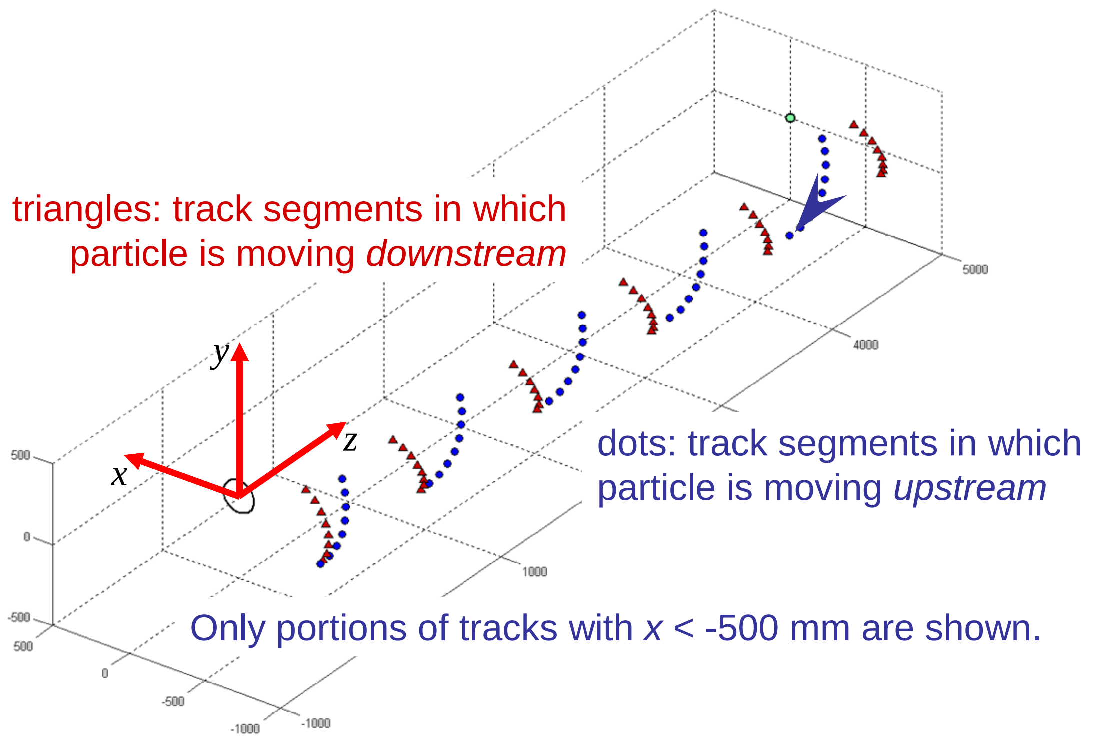


Upstream-moving (solid) and downstream-moving (dotted) electron trajectories.

The stopping target, indicated as a circle centered at (0, 0, 0) in the diagram, is near the point at which the track is reflected back downstream. Note that the general clockwise sense of rotation is preserved by the reflection.

I used MatLab to generate the electron trajectories, solving for the exact helical motion associated with the magnetic field at the particle's location, and advancing in small time steps of 0.1 nsec to build up the full path followed by the particle. As a result, the trajectory shown in the figure should be fairly accurate.

The next figure shows the same electron's path, but with portions of the trajectory with $x > -500$ mm blanked out. It is easier to see in this figure that the pitch angles reverse sign for the upstream- and downstream-moving segments of the track. As before, the electron is injected from the downstream end at the location marked by the small filled circle.



Upstream-moving (dots) and downstream-moving (triangles) electron trajectories, showing points for which $x < -500$ mm.

A cleverly designed magnetic line through which the calibration beam would pass before entering the spectrometer might make it possible to paint the entire electron phase occupied by the $\mu^- N \rightarrow e^- N$ electron signal without reconfiguring the linac.

But why a Project-X (or ILC) cryomodule?

The Project-X and ILC cryomodules are both superconducting assemblies using 1.3 GHz Niobium accelerating structures. The designs differ slightly—the Project-X cryomodules accelerate protons, so the phasing of cavities must accommodate the non-relativistic proton velocities, rather than the relativistic speeds attained by electrons after only a few centimeters of acceleration. Particle energies leaving the first cryomodule can be as high as ~200 MeV, more than adequate for a calibration linac for Mu2e as long as the proton- vs. electron- phasing issues can be addressed.

I have worked with Shekhar Mishra on ILC matters for some years, and we touch base when the opportunity arises, even though budgetary problems have made the fortunes of the ILC uncertain. I spoke to Shekhar last week about the mess we're in, and was pleased to learn that the lab is moving forward on production of cryomodules. It is currently hoped that six or seven will have been completed at Fermilab by the year 2010.

I asked him if it would be possible for a spare cryomodule to be made available to Mu2e for use in a calibration linac.

Shekhar said yes, and that they expected to have an extra one available by 2010.

So that's why.

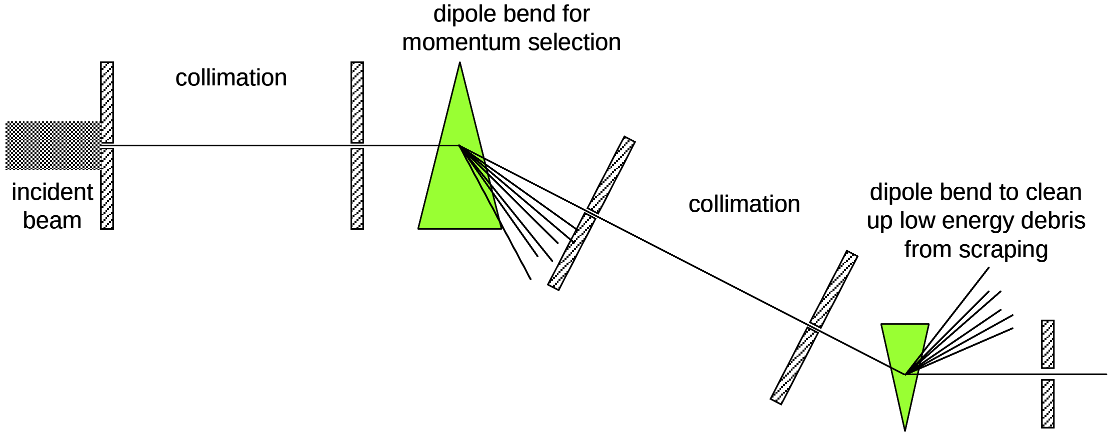
Some thoughts on calibration beam collimation, energy determination, and injection optics

Cryomodule linac electron bunches

Let's assume that the properties of electron bunches leaving a cryomodule can be tuned to be roughly the same as those accelerated by the AØ photoinjector, except for the large difference in energy. (The photoinjector beam energy is 16 MeV.) In that case, an electron bunch from a cryomodule would contain ~10^9 electrons with a transverse spot size of about a millimeter, and a bunch length of less than a millimeter. The exit time of a bunch from the cryomodule could be measured (non-destructively!) with sub-picosecond accuracy.

Flux reduction and momentum selection

I expect that most calibration data will be taken with electrons being injected one at a time into the spectrometer. One way to obtain this reduction in flux is to collimate the beam tightly. An arrangement using pairs of slit collimators placed on either side of a dipole bend as shown in the next figure. This could also serve to narrow the momentum range of calibration electrons presented to the spectrometer. Note that there are no active elements that would interfere with the calibration electron on its way to the Mu2e detector. As a result, electrons that do not scatter from the edges of collimation slits do not lose energy en route to the detector.



Flux reduction and momentum selection using slit collimators and dipole magnets.

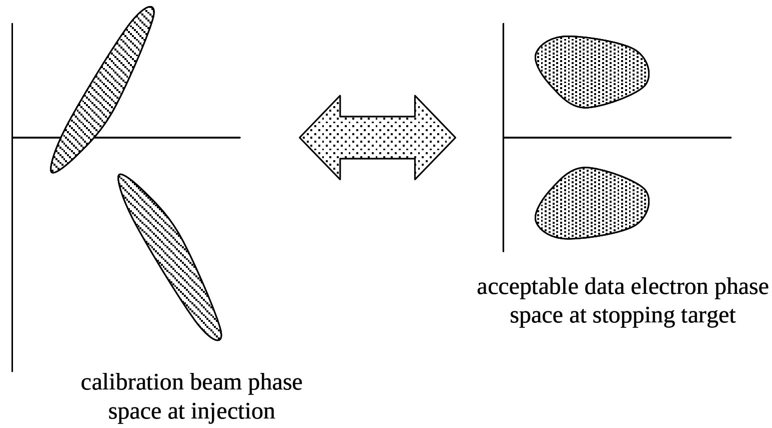
Painting the appropriate region of phase space with calibration electrons

In order to provide useful information about spectrometer energy scale and resolution, a calibration electron must be injected into the Mu2e spectrometer “on orbit” so that, upon reflection from the stopping target region, it follows a trajectory that is typical of signal electrons.

The boundary of the phase space volume that defines the spectrometer’s useful geometrical acceptance can be parameterized as a hypersurface in a five-dimensioned space spanned by the 105 MeV/c electron’s production coordinates in the region near the stopping target and the polar and azimuthal angles of the electron’s momentum leaving the target.

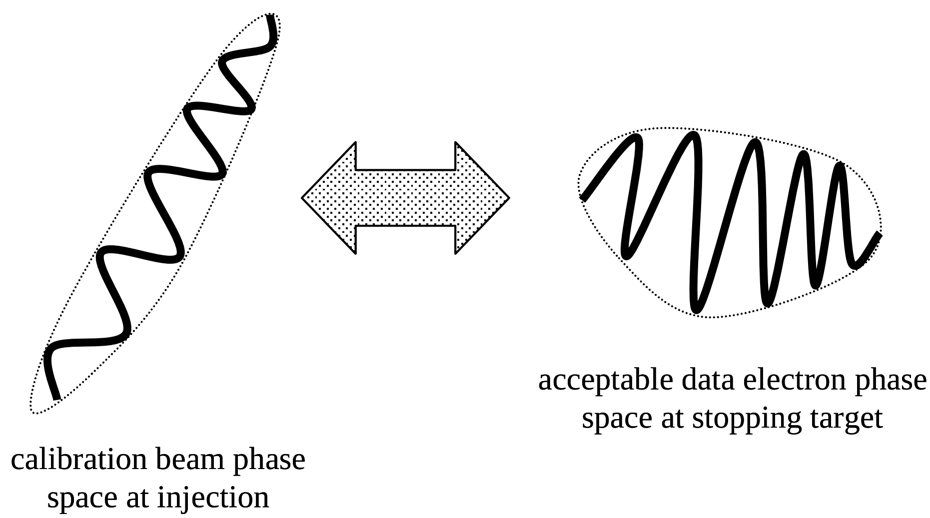
Neglecting energy loss and other disruptive processes so that Liouville’s Theorem holds, it should be possible to establish a one-to-one correspondence between points in the phase space distribution characterizing the calibration beam at injection to most points in the phase space of acceptable data electrons leaving the stopping target. In plainer language, it should be possible to populate nearly the full space of trajectories followed by data electrons that pass through the spectrometer by injecting calibration electrons in an upstream direction along suitable paths that begin at the downstream end of the apparatus. (Calibration electron paths in which the electron strikes the downstream edge of a screw-sense calorimeter vane will not participate, however!)

This is shown schematically in the next figure.



A schematic representation of phase space mapping between data electron coordinates (in the vicinity of the stopping targets) and calibration electrons at injection.

Note that it is probably unnecessary to "paint" the full phase space volume occupied by acceptable data electrons. As long as the detector's resolution and efficiency change sufficiently slowly over the data electron phase space, sampling the phase space with calibration electrons should be adequate. This is shown (again schematically) in the next figure.



Phase space mapping between data electron coordinates and calibration electrons at injection when the calibration samples, rather than painting the full phase space.

It would be convenient to find a technique that mapped a simple scan of one variable in linac beam parameter space into a complex curve in data electron phase space. This is a subject for further exploration.

A few of the advantages

I assume that adequate suppression of dark current from the linac's electron source is straightforward, allowing complete confidence that the linac never launches an electron into the Mu2e spectrometer unless so instructed.

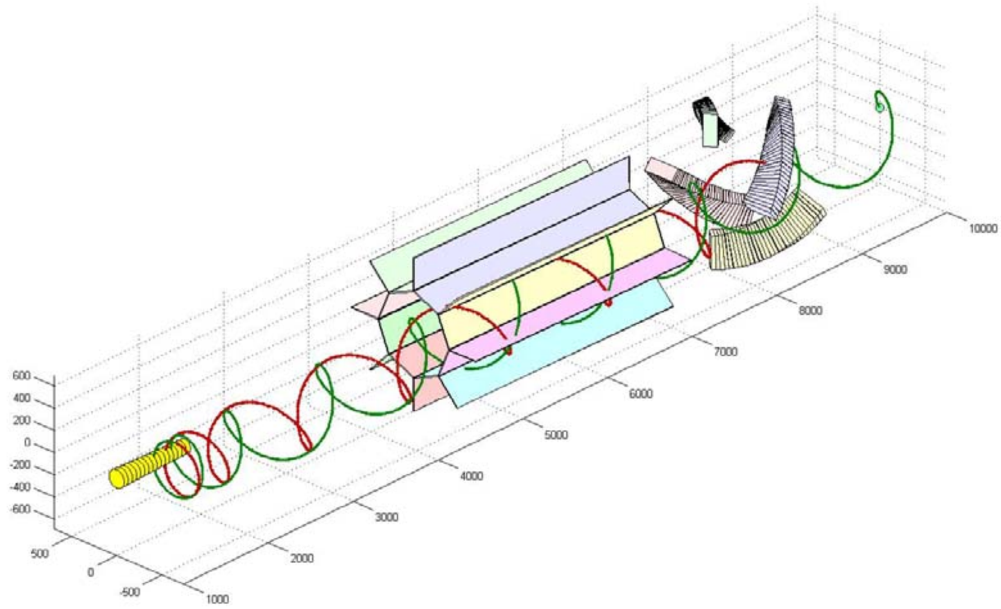
I expect that no reconfiguration of the Mu2e spectrometer will be needed to record a calibration event, so that calibration electrons can be injected as desired, even while the stopping target is being illuminated with muons. This provides a way to determine detector calibrations *in situ*, during actual data taking.

Track momenta are measured *twice* for calibration electrons, once for the upstream-moving segment of the track, and a second time for the downstream-moving portion of the track. This allows systematic comparisons that are likely to be informative.

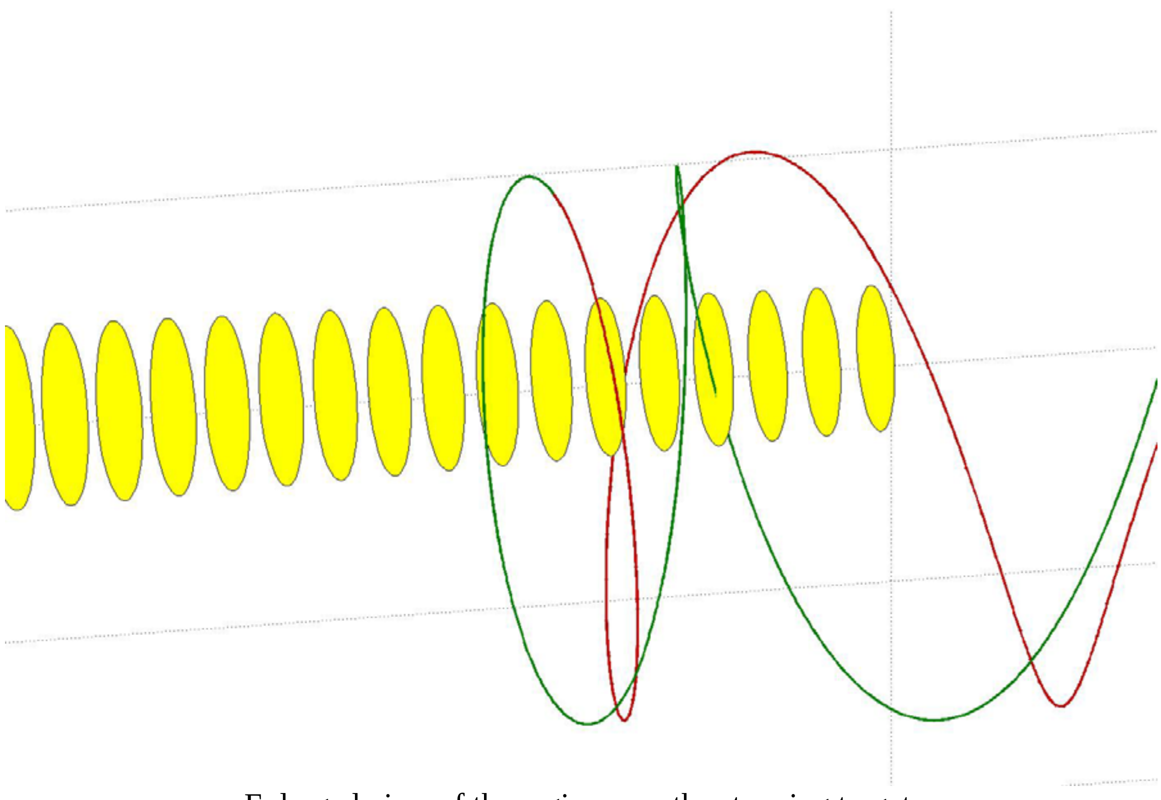
A more realistic representation

In the following figures a 105 MeV/c electron with the same initial direction is projected into a version of the Mu2e spectrometer that is similar in geometry to the MECO detector except for the calorimeter reconfiguration. The magnetic field in the spectrometer is a close approximation to that obtained by running a Biot-Savart Law calculation of the fields made by a solenoid whose current density varies with z. In the calculation, currents were adjusted to produce a 2 T field well upstream of the stopping targets and a 1 T field somewhat downstream of the stopping targets. The z component of the magnetic field varied from 1.61 T at the upstream end of the stopping target to 1.30 T at the downstream end of the target. Near the target, the radial component of the field varied from 0 (on the axis of the solenoid) to approximately 0.14 T at a radius of 700 mm.

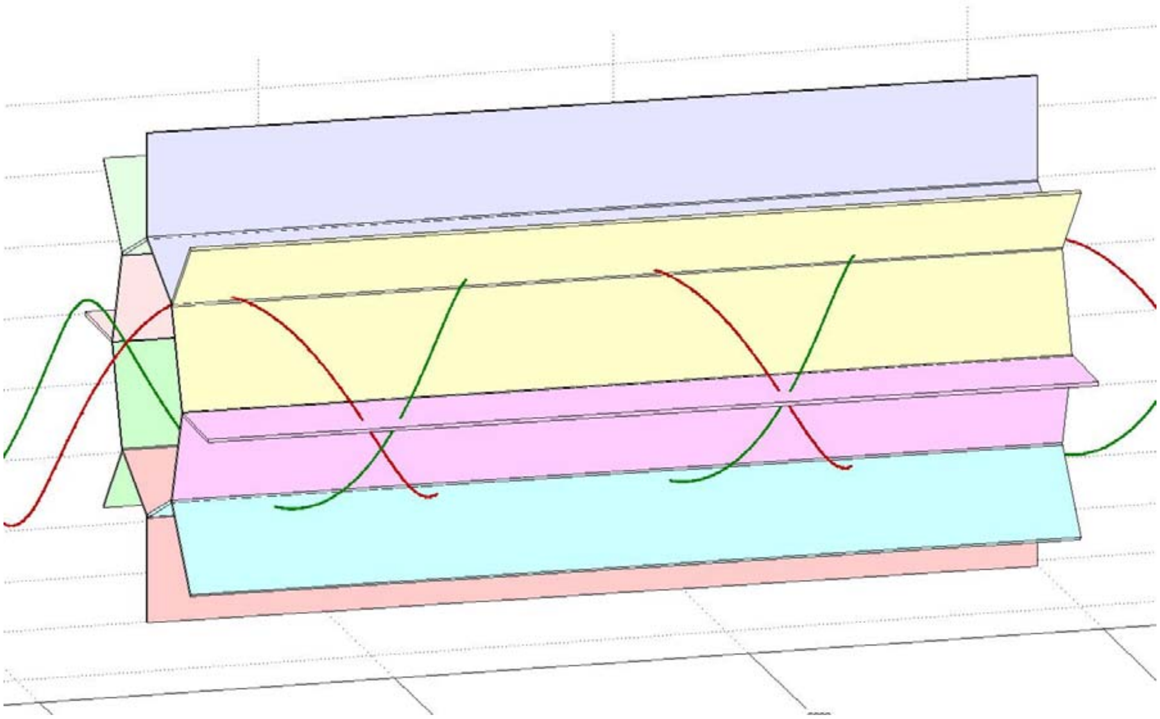
The red portion of the track is moving downstream (to the right) while the green portion is moving to the left.



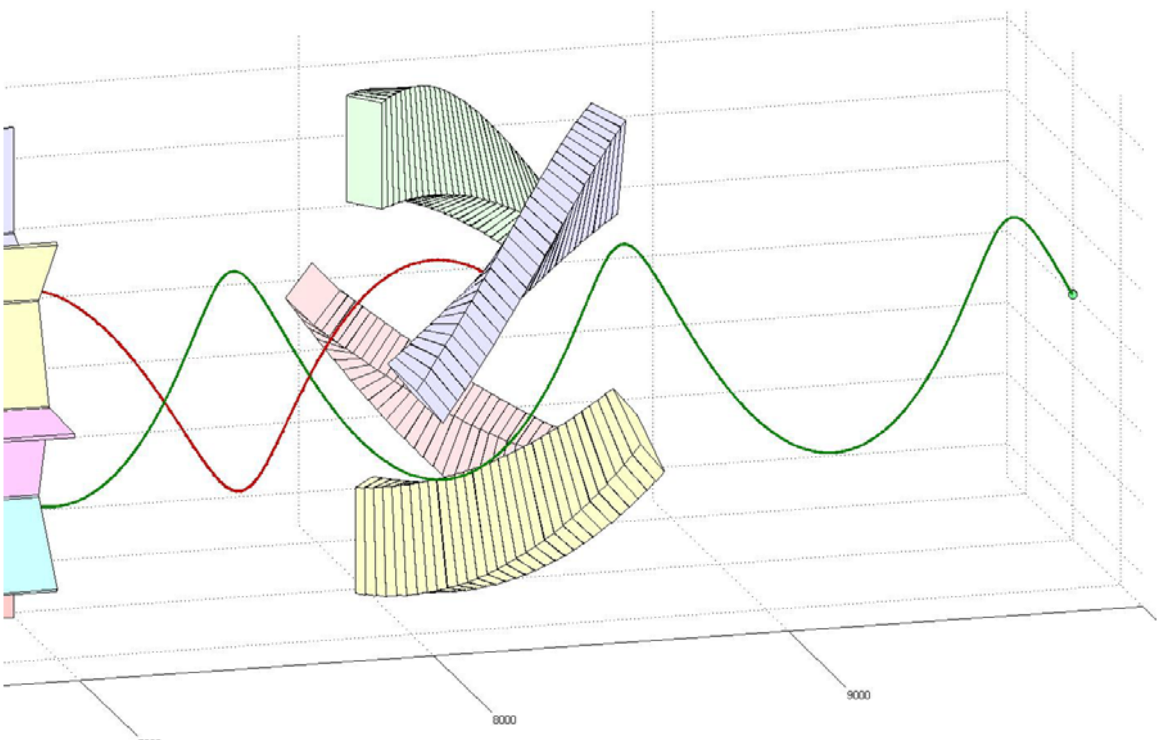
Downstream injection of a 105 MeV/c calibration electron.



Enlarged view of the region near the stopping target.



Enlarged view of the region near the straw tube tracker.



Enlarged view near the calorimeter.

What's next?

Perhaps this:

1. Monte Carlo studies to confirm that this really would work.
2. Discuss this inside the collaboration, then raise the issue with Fermilab. We will want the lab to know of our interest in using a linac for Mu2e calibration.