Muon Diagnostic Issues for the Neutrino Source

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This note describes some of the constraints on muon diagnostics for the neutrino source and considers useful options. Many of these issues will also apply at some level to the design of the muon cooling experiment.

Although measurements of muon beams have been made for years, the high precision, high intensities, limited access, and large backgrounds associated with the cooling environment may make the required measurements of the muon beam challenging. The primary problems seem to be associated with tuning and operating of the transverse cooling sections. At the upstream end of the cooling line, the total number of secondaries produced at the target will make any measurement of muons difficult, however at the downstream end of the cooling line, once pions and other particles have decayed or been removed by collimation, solenoidal focusing, momentum cuts or absorption, measurements using standard techniques should be much easier. Once through the cooling line, the expected flux of $\sim 2 \times 10^{12}$ muons would be very similar to existing electron or proton beams.

Ideally one would like very high precision measurements of the complete 6 dimensional muon phase space at a variety of locations along the cooling line and accelerator system. In practice, however, the only experimentally available quantity which can be measured in a straightforward way is the beam profile. We assume then that the primary diagnostic technique used in the cooling line will be to measure the transverse bunch profiles at two points separated by a betatron phase advance of roughly 90 degrees, which can be used to reconstruct the transverse emittance from the measured widths of the distribution, and an assumed value of the beta function for the solenoid geometry. The longitudinal emittance would be most accessible using measurements of bunch shape made one fourth of a synchrotron period apart. Since emittance and beam distributions produced at the particle source should be stable, destructive detectors, which could be inserted and retracted might be useful. A variety of detectors could be used for measuring the profile of the high intensity muon beams such as including Segmented Wire Ionization chambers, (SWICs), Secondary Emission Monitors (SEMs), or scintillation screens.

The tuneup problem is simplified somewhat since the total number of variables in a cooling section, or even the whole cooling line, is small and optimization of the system should not require large deviations of these parameters from calculated parameters. In addition one would expect these variables would change slowly down the length of the cooling line. The externally adjustable variables in each FOFO section would perhaps consist of only four coil currents, two electric fields and two rf phases, together with whatever trimming coils would be included. Thus optimization of a complete system should be simple, in principle.

Since one is unable to follow individual particles, the measurement of emittance is determined from $\varepsilon = \langle x \rangle^2/\beta$. Following Greg Penn's note[1], the emittance is,

$$\varepsilon_N = [\langle x^2\rangle\langle p_x^{\,2}\rangle - \langle xp_x\rangle^2 - \langle xp_y\rangle^2]^{1/2} /mc,$$

where the first term in the bracket refers to the classical measurement of an upright emittance ellipse at a beam waist, and the other two terms are due to the correlations associated with variations in the betatron phase and mechanical angular momentum[1]. It may be desirable to be able to move the diagnostics in some limited range along the beamline in order to precisely locate the beam waists. The measured emittance will depend on the β function and its longitudinal dependence.

The longitudinal development of the beta function is determined by Penn from the equation,

$$2\, \beta_\perp \beta_\perp'' - (\beta_\perp')^2 + 4\, \beta_\perp^{\,2}\, \kappa^2 - 4\, (1 + L^2) = 0,$$

where $L = \langle L_{canon}\rangle/2mc\varepsilon_N$ is the angular momentum term and $\kappa = qB/2p_z$, gives the momentum momentum dependence, where q, B, and p_z are the charge, solenoidal field and longitudinal momentum. Since the proposed lattices, shown in Fig 1, have rapidly changing magnetic field and $\beta_\perp$ functions in the accessible regions between absorber and linac, they can be expected to have strong chromatic and angular momentum dependence.

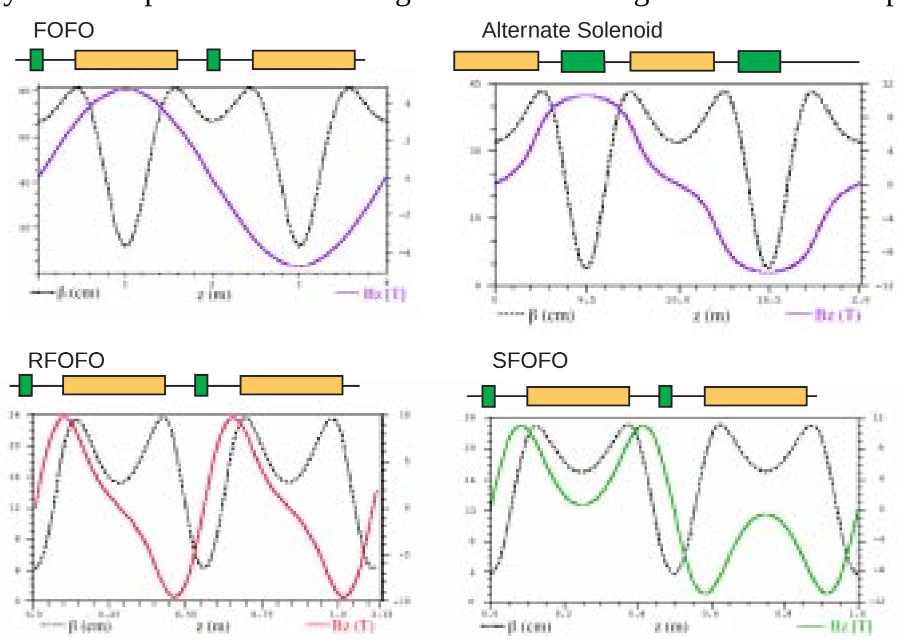

Figure 1, The magnetic field and beta functions for the cooling lattices.

The dependence of a simple FOFO system to mismatches in momentum and angular momentum are shown in Figure 2, where beams of different momenta are introduced into a section designed for L = 0, and p = 196 MeV/c. These mismatches partially determine the precision of an emittance measurement.

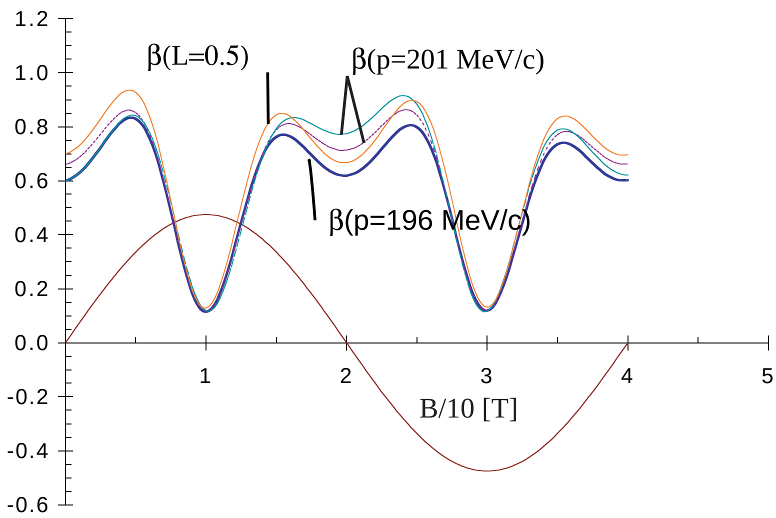

Figure 2, The effect of 2.5% momentum fluctuations and ΔL = 0.5 in a FOFO.

Since measuring the emittance requires a knowledge of β functions, and β depends on the momentum and angular momentum *spectra*, the measurement of beam emittance may be quite complicated. The possibility that both the transverse and longitudinal emittance are not radially symmetric must also be considered. The use of special diagnostic sections, without linacs or absorbers, where a more extensive range of measurements, perhaps including momentum and mechanical angular momentum spectra, could be made thorough one complete cell, might be desirable. These sections could perhaps be used to optimize many cells of the cooling line.

There are a number of measurements that seem to be required, starting with:

- Alignment of components. This could be done with pencil beams on axis, since the normal muon beam will fill the aperture.
- Initial matching of the cooling line. Since mismatches due to momentum errors could propagate through many cells, it will be necessary to insure that the cooling line starts matched to the beam momentum, which seems to require extensive measurements at the upstream end of the cooling line, with comparatively dirty beams (with respect to both optics and backgrounds).
- Matching of the beam down the line. Cooling will be less efficient if the focusing is not correct, one should try to match and optimize each cell.
- Measurement of the emittance after a number of sections of cooling. This would be used to optimize significant lengths of the cooling line. Since a FOFO

cooling line is fairly long, it may be desirable to leave the rf and absorbers out of two or three diagnostic cells at the end of the cooling line and perhaps have diagnostic sections scattered through the cooling line.

A variety of other measurements such as beam momentum and angular momentum distributions would be very valuable, and might require dispersive sections, which could perhaps utilize bent solenoids.

Precision, dynamic range

The cooling section consists of a number of accelerating and attenuation sections. The approximate size of the cooling effect in each section, in the absence of multiple scattering and straggling, two dimensional transverse emittance will change by an amount

$$\Delta\varepsilon/\varepsilon = 1/\beta^2\, \Delta E/E = 1/\beta^2 l\, (\mathrm{d}E/dx)/E \sim 17\%/\mathrm{m}_{H2}$$

where $\Delta\varepsilon/\varepsilon$ is the fractional reduction in emittance, β and E are the muon velocity and total energy, dE/dx is the energy loss in liquid hydrogen (28.6 MeV/m), l is the hydrogen absorber length, and the beam dimensions $x = \sqrt{(\beta\varepsilon)}$, will change by the square root of that amount. With a recent example of the FOFO lattice[2] where the absorbers are 0.14 m long, the emittance would change by 2.4% without scattering, and the beam dimensions would change by 1.2% per section. It seems difficult to measure the emittance change from single stages with sufficient precision to be a useful. On the other hand precise measurements of a number of sections seem more straightforward.

The dynamic range of diagnostics is important for determining the shape of distributions, losses and backgrounds. The exact requirements are difficult to determine at this time, however loss rates require measurements of particle densities 3σ away from the center with significant precision.

Single Particle / multiparticle

While measurements of the whole bunch will be done during normal operation of the facility, it may be desirable to maintain the capability of using single particle or very small emittance beams for checks of alignment and cleaner measurements of beam optics. Single particle diagnostics require measurements from small signals, and thus would be more sensitive to rf cavity backgrounds. Single particle diagnostics are also be very desirable for a muon cooling demonstration.

Alignment

The alignment of components in the cooling channel has been extensively examined by Lebrun for the Alternate Solenoid case using DPGeant, with the conclusion that coil misalignments of 0.5 mrad significantly degrade the cooling[3]. These misalignments introduce dipole field components on the order of 10 - 100 Gauss which deflect the beam. Beam based alignment has been used extensively in linear colliders to solve similar problems[4]. This could be done either using the centroid of the full beam or a specially defined small emittance diagnostic beam which could be used to define the beam axis.

Backgrounds

While low energy pions will be the dominant species in the decay line, the target solenoid at 50 mr to the proton beam will also collect high energy protons, K's, deuterons, tritons and heavier nuclei in significant numbers, as well as electrons and gammas produced from showers in the target. These particles and the hadronic and electronic showers they produce could cause a number of problems with diagnostics.

The total flux of particles produced at small angles and captured in the decay solenoids has been calculated by Mokhov [5] and is presented in Figure 3. This data shows that any meaningful measurements near the target, bunch rotation section or the early stages of cooling will be very difficult due to backgrounds.

Since the decay and phase rotation solenoids will confine all particles with $p_\perp$ < 0.02 GeV/c, the secondaries can have very high energies, and a variety of particles such as K's, T's and d's could cause a variety of problems.

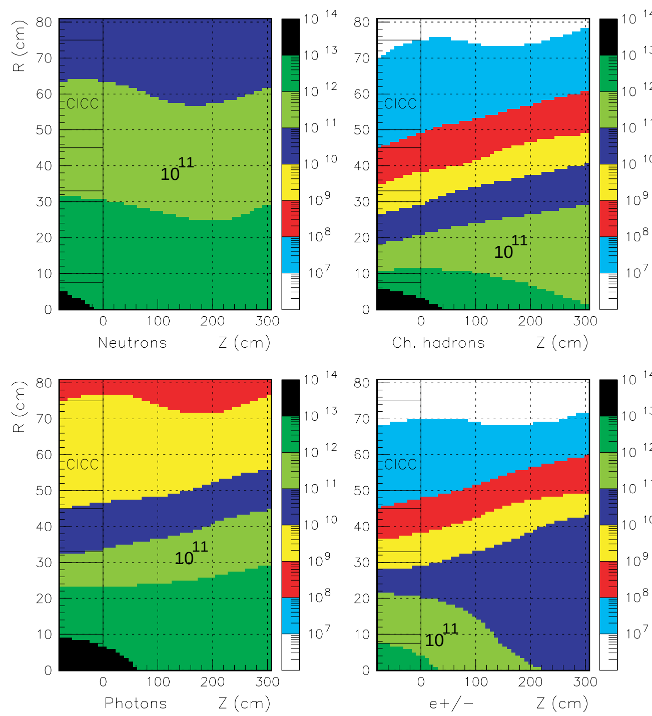

Figure 3. Particle Production, #/cm^{2}s from 10^{14} p.

Table I

Particles/proton	at 3 m	15 m	cause	can be reduced by
neutrons	3.9	0.16	mostly spallation	distance
hadrons$^\pm$	1.8	0.55	pions and H. E. protons	bent sol., timing
$e^\pm$	0.3	0.04	from $\pi^0 \rightarrow \gamma\gamma \rightarrow$ shower	bent sol., timing
γ's	10.7	1.2	"	distance
μ's	0.18	0.4	from pion decay	-

The spectrum of secondary protons has been calculated at 19.5 GeV by Grote, Hadedorn and Ranft[6]. (Better data exist.) Since the solenoid acceptance angle, $\Omega \sim (0.2/p)^2$, decreases with momentum, the acceptance at high momenta is somewhat reduced but, at $\theta \sim 50$ mr, the spectrum of captured protons extends to the full beam energy. This spectrum is shown for 1 - 120 mr production angles in Figure 4. High momentum protons are particularly troublesome because they would produce many secondaries in hadron showers which extend the length of the cooling line, contributing background to measurements of the beam edges. Bent solenoids in the decay region might remove backgrounds by introducing a rough momentum analysis in the line to high momentum tails without altering the acceptance for low energy muons[7]. Timing would also separate these backgrounds.

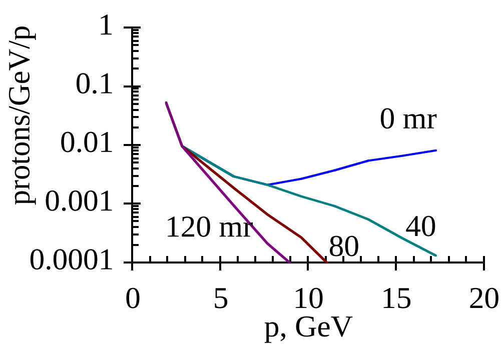

Figure 4, Spectra of protons captured in the cooling line as a function of production angle, for 19 GeV protons.

Loss mechanisms

Measurement of losses from the cooling channel is an important aspect of the diagnostics problem, since muons can be lost either transversally or longitudinally and loss mechanisms can involve transport through a number of cooling sections after the particles have left the stable region of phase space. Loss rates can be approximated by knowing the density of particles in the extremes of the transverse distributions, and near the separatrix of the longitudinal distribution. Since particles move more slowly near the separatrix, the losses (shown in Figure 5) should be measurable from bunch shape, particularly the edges of the bunch, at an rf frequency of 200 MHz, using fast timing. SEM monitors, described below, could be useful.

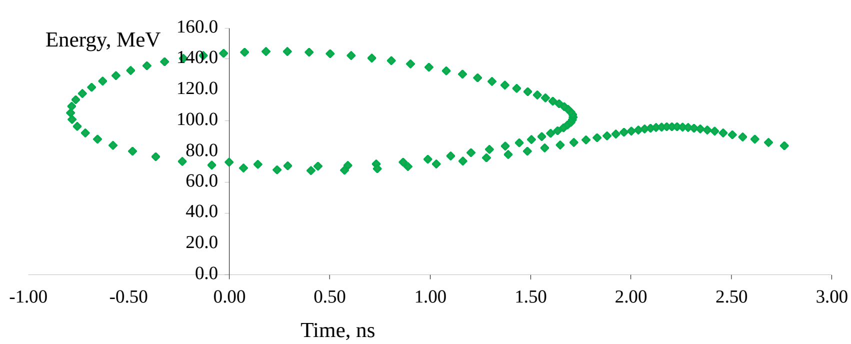

Figure 5, Longitudinal motion of lost particles near the separatrix.

Timing requirements.

Very good timing information is desirable for a number of reasons: 1) Since the muons will be accompanied by electron, proton and pion backgrounds, timing will be one of the easiest ways to discriminate between muons and backgrounds. 2) Bunch profile measurements are perhaps the easiest way of estimating the longitudinal phase space and density of the muon bunch. 3) Timing is can be utilized to make very precise momentum measurements over long distances. 4) Loss rates should be experimentally measurable using longitudinal bunch shape, which for 805 MHz cavities would require ~0.1 ns resolution. 5) In addition, at the 0.1 - 0.2 ns level, timing information may be generated fairly cheaply. The scale of bunch is shown in Figure 6, where the time development of the bunch as a function of distance from the target is shown relative to the time of very high energy protons or electrons in the beam, assuming phase rotation takes place at 75 m. Hadron showers will produce slow particles which will tend to fill the gap.

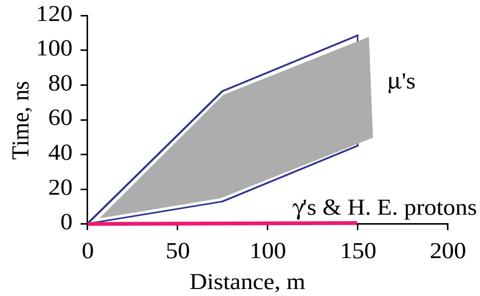

Fig. 6. Development of μ bunch.

Since the cooling line will consist of linacs and absorbers with metallic windows, the wakefields of the beam will be strongly affected by the longitudinal structure of the volumes in which they are measured, thus wall current monitors will give a mixture of longitudinal and transverse information and will not give precise beam profile information.

Acceptance

The muon beam in the cooling line is very large and has a very large divergence, thus the nontrivial requirement that the diagnostics are sensitive to the entire beam. Cherenkov counters, for example which accept solid angles approaching one steradian are difficult to design [8].

The physical environment

solenoidal field

The solenoidal field, which will continuously vary (reverse) over small distances while the maximum field increases over the range 2 - 15 T down the length of a collider cooling line, will affect the behavior of many diagnostics. The beta function will be hard to calculate.

rf field/ rf cavity backgrounds

The cavity windows would completely prevent any rf fields from impacting the detectors. On the other hand, the dark current electrons accompanied by a high flux of x-rays should easily penetrate the windows and any hardware associated with the hydrogen absorber. An experiment is being done on this subject at Argonne[9]. (More experimental information should be available soon.) In general, the solution to background problems is to make the signal stronger, thus bunched beams are favored over single particle beams.

Mechanical requirements

The diagnostics will be exposed to intense beams for a very long time thus they must be rad hard. Cooling must be provided to remove the heat generated by ionization heating. These devices may be partially destructive to the beam so they should probably be removed for normal running. Motion of diagnostics along the beam should be considered.

Access

There are significant constraints on access to the beam. Muon cooling is most efficient if the absorbers and accelerating cavities occupy regions of smallest β (highest field) and largest β, (lowest field). In addition, the high cost of the cooling line magnets and rf system requires that the space for cooling be utilized as efficiently as possible, thus space most easily used for diagnostics tends to be regions where the magnetic field and the β function are changing at a maximum rate. The present configuration, shown in Figure 7, leaves little space for diagnostics. Access for maintenance must also be considered.

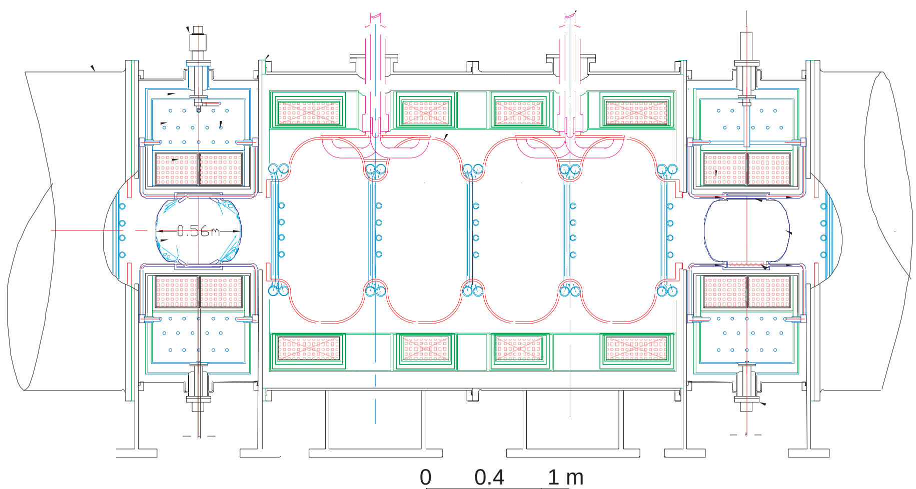

Figure 7. The Alternate Solenoid configuration. Space for diagnostics is limited. The geometry for the FOFO is different, but the problems are similar.

Diagnostic Options

Time Projection Chambers (TPC's)[10], Cherenkov counters[8] and fast timing systems[11] are being developed from high energy physics technology for single particle measurements in the MUCOOL setup. These three systems have been described elsewhere. The intense beams of the ν source/collider system will tend to rely more on systems which are compatible with very high beam powers.

One assumes that devices which introduce minimal integration times would be much more desirable, so it seems most useful to consider SEM systems first.

An example of a SEM profile monitor similar to one which could be used in the muon cooling line is shown in Figure 8. This system is used on the IPNS accelerator to monitor the extracted beam profile. The signal size is given by the relation, $V = N\delta/C$, where V is the signal voltage, δ is the secondary emission coefficient, C is the appropriate capacitance and N is the number of protons hitting the probe element. At the IPNS, each of 32 detector elements is a Cu bar, 0.317 cm wide and ~0.25 cm thick, and charge is integrated using 30 m of RG-174 cable. The voltages produced are in this system are on the order of 200 mV, giving an electron secondary emission coefficient of $\delta = 0.13$. Since the signal is produced directly from the beam current, this method is "infinitely" fast, if the impedance of the probe (a 50Ω stripline?) is matched with the cable. The signal can be recorded using a sampling scope, which could have a maximum bandwidth of 50 Ghz[12].

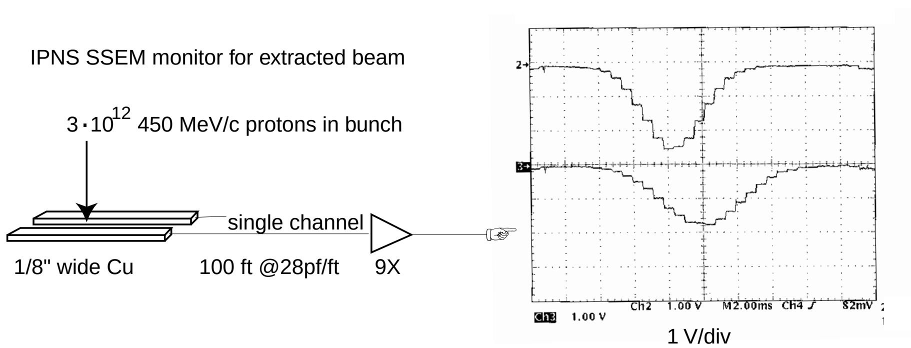

Figure 8. The IPNS SEM system

The IPNS also uses Segmented Wire Ionization Chambers (SWICs) for beam profile measurements. The devices have one atmosphere of He, and the currents are collected onto gold coated tungsten wires. According to Sauli[13], typical pulses from ionization chambers are on the order of 10 ns.

Although the number of particles and the bunch structure of the IPNS extracted beam is similar to the cooling line, the 450 MeV/c protons of the IPNS would produce about eight times the ionization heating expected from the muon beam. The large copper probes used in the SEM detectors overheat in this beam when the system is used at 30 Hz, but gold coated tungsten wires used for the SWIC system have operated stably for almost 15 years or roughly $6{\cdot}10^9$ pulses ($2{\cdot}10^{22}$ protons).

The impedance of a stripline is given by the expression [14]

$$Z = \frac{\sqrt{\mu_0/\varepsilon_0}}{w/b + 2/\pi\ \left[1 + ln(1 + \pi w/2b\ )\right]}$$

where μ_0 and ε_0 are the permeability and permititivity constants, the width, thickness and gap for the stripline are w, t, and b. Note that the impedance of the line remains constant if the width, thickness and spacing are increased proportionally, although the signal would be proportional to the area seen by the beam. Thus it seems possible to produce spoon shaped probes that would be sensitive to timing at the center of the beam without significant sensitivity to the beam's transverse dimensions. These are shown in Figure 9.

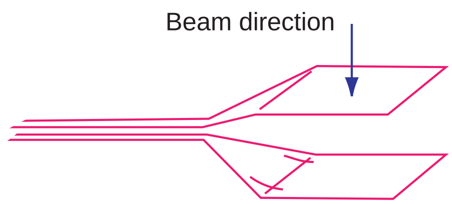

Figure 9. A high frequency pickup. The signal will be proportional to the area seen by the beam, thus the leads should make a minimal contribution to the signal. Rotating the leads by 90^0 would further reduce pickup.

In principle, direct measurements of emittance, momentum and mechanical angular momentum spectra are possible with collimators using methods like pepperpots. At low momenta, collimators work well but the measurements would be somewhat more difficult than beam profiles. With the shorter pulses like we would expect in the collider, the voltage from a SEM monitor will be determined by the capacitance of cable lengths comparable to bunch dimensions rather than the total cable dimensions, thus signal sizes could be much much larger.

Conclusions

Secondary emission monitors seem to satisfy the requirement of the muon cooling diagnostics better than other alternatives. They are simple, fast, produce large signals and seem stable.

References:

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