Wedge Absorber in MICE

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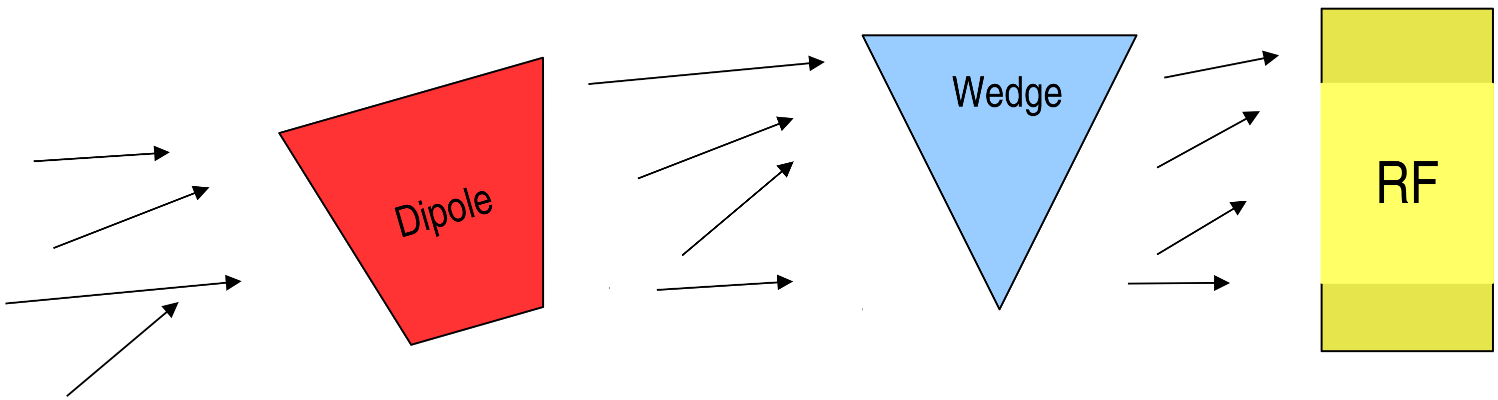
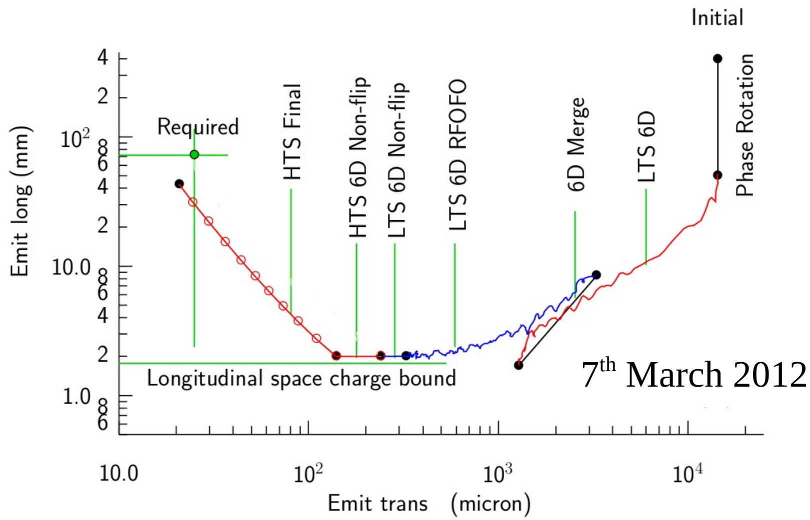
Demonstration of longitudinal Cooling

- MICE will demonstrate **transverse cooling**
  - Key technology for Neutrino Factory
  - Key technology for Muon Collider
- Muon collider relies also on **emittance exchange**
  - Muons acquire a position-energy correlation from dipole
  - Muons traverse a wedge shaped absorber where the correlation is removed
    - Energy spread transferred to position spread
    - Exchange of longitudinal emittance to transverse emittance
  - Key technology for Muon Collider



Muon Collider Cooling

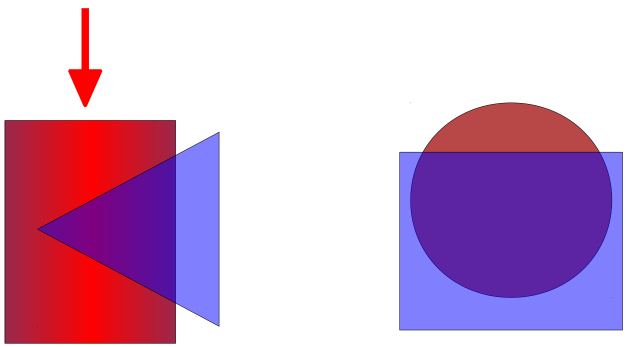
- Any Muon Collider relies heavily on emittance exchange
  - Lower longitudinal phase space means higher frequency RF
  - Merge of microbunches to increase luminosity
- Implementation in MICE
  - Effect of dipole is well known
  - Effect of RF is well known
  - (Engineering with an absorber is demonstrated by MICE Step V)
  - Demo of a beam traversing a wedge has not been done
- Can we put a wedge-shaped absorber in MICE and see longitudinal emittance reduction?
- Topical: What if we can't afford LiH

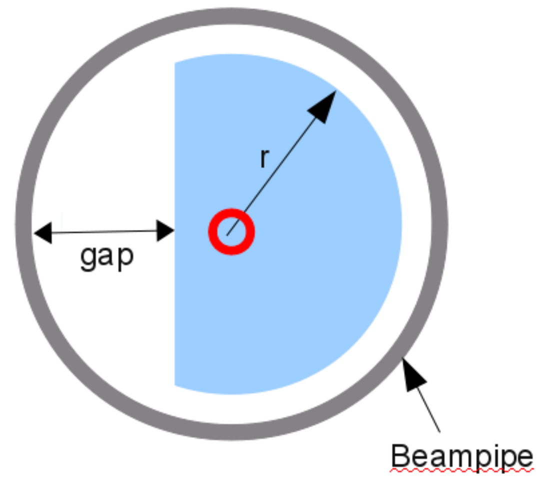


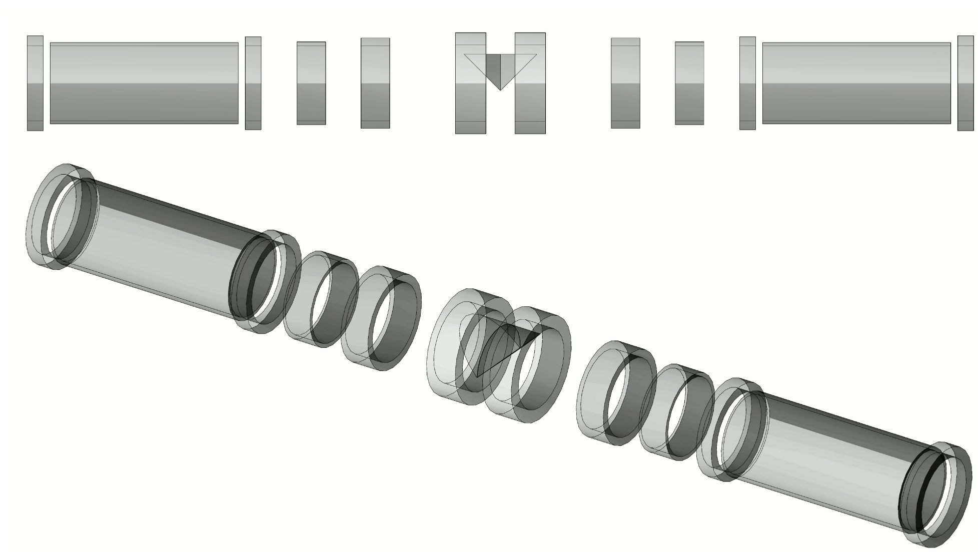
Wedge Geometry

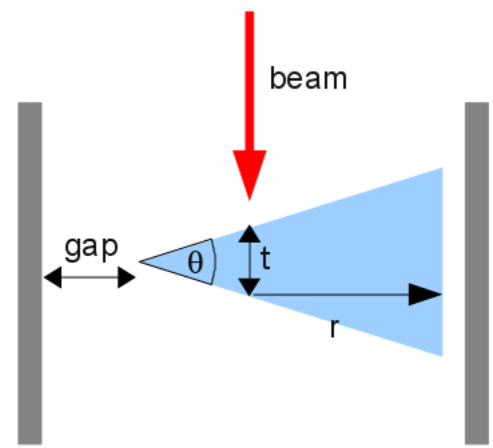
Geometry of wedge in MICE

- Wedge is an intersection of a cylinder and a prism
- Introduce dispersion by beam selection



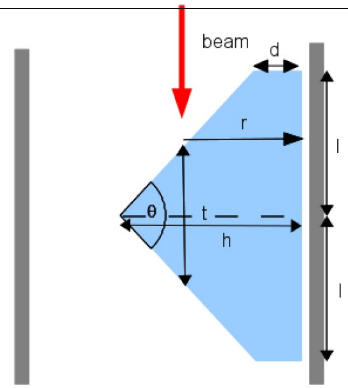






Parameters

Wedge



material	LiH	LiH	LiH	C_2H_4	C_2H_4	C_2H_4
θ [°]	30	60	90	30	60	90
r [mm]	225.0	225.0	225.0	225.0	225.0	225.0
t [mm]	75.4	75.4	75.4	60.5	60.5	60.5
h [mm]	365.7	290.3	262.7	337.9	277.4	255.3
l [mm]	98.0	167.6	225.0	90.5	160.2	225.0
d [mm]	0	0	37.7	0	0	25.1
mass [kg]	12.16	16.27	17.7	12.4	17.3	19.0

Beam

Parameter	Value
Reference P [MeV/c]	200
Transverse emittance [mm]	6
Transverse β [mm]	420
Transverse α	0
Longitudinal emittance [mm]	90
Longitudinal β [ns]	10
Longitudinal α	0
RMS Energy Spread [MeV]	25.1
D_x [mm]	200
D_y [mm]	0
D'_x	0
D'_y	0
Number of μ^+	10000

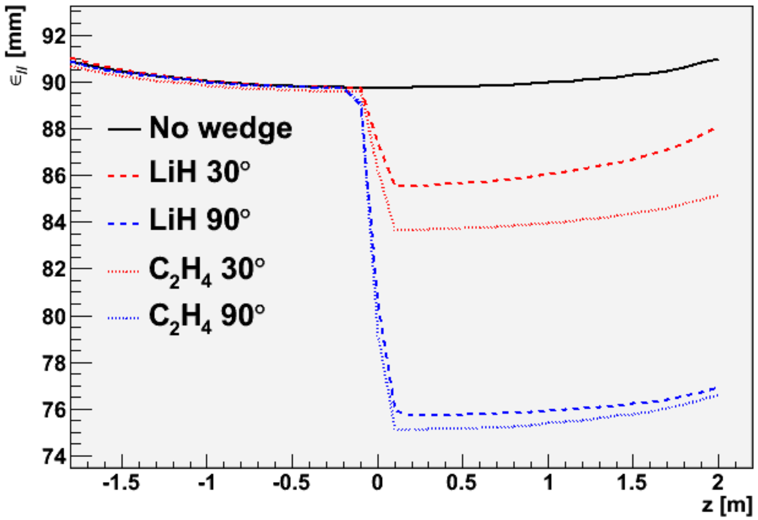
Coils

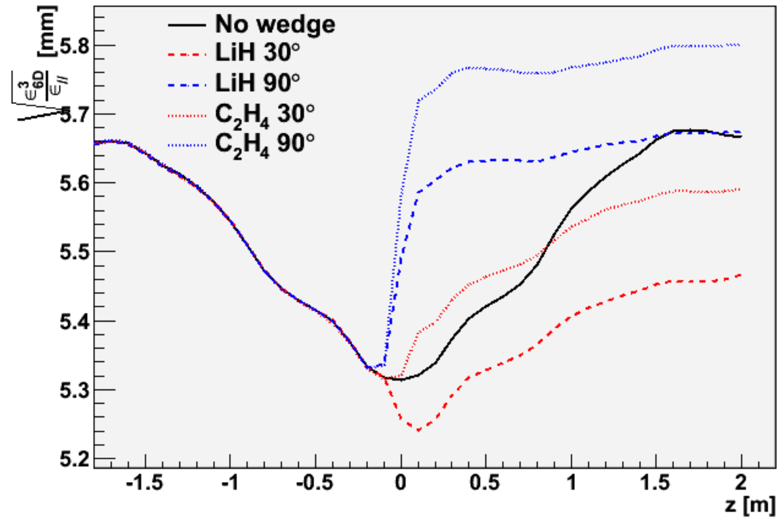
Coil	Length [m]	Inner Radius [m]	Radial Thickness [m]	Mean Z [m]	Mean R [m]	Current [A/mm^2]
FC1	0.2100	0.2630	0.0840	0.205	0.3050	113.95
M1	0.2012	0.2580	0.0447	0.861	0.2804	118.56
M2	0.1995	0.2580	0.0298	1.30105	0.2729	137.13
E1	0.1106	0.2580	0.0596	1.701	0.2878	127.37
C	1.3143	0.2580	0.0213	2.45105	0.2687	152.44
E2	0.1106	0.2580	0.0660	3.201	0.2910	135.18

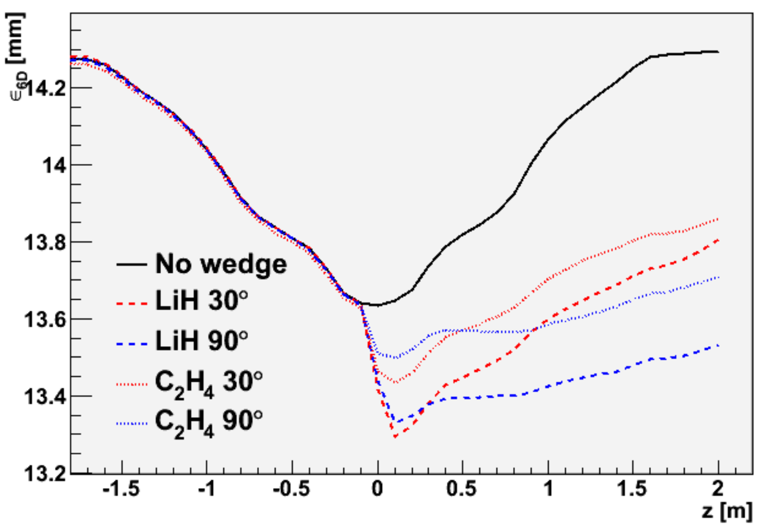
Aims and Methodology

- Aims
  - First priority is to observe longitudinal cooling
  - Second priority is to observe longitudinal and 6D cooling
  - Third priority is to observe transverse, longitudinal and 6D cooling
  - Fourth priority is to get cooling over a broad range of conditions
- Candidate geometry
  - Can handle any wedge opening angle up to about 90^{o}
    - I take this as a maximum (though might be able to go higher)
  - Consider LiH, Polyethylene $(C_2H_4)_n$
  - Thickness chosen to give comparable energy loss to lH_2 absorber
    - Thicker wedges excite worse non-linearities

Cooling Signal at 6 mm



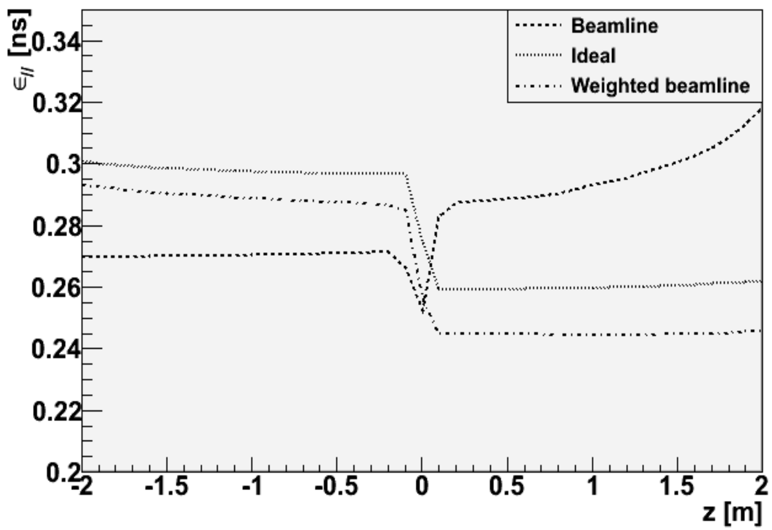


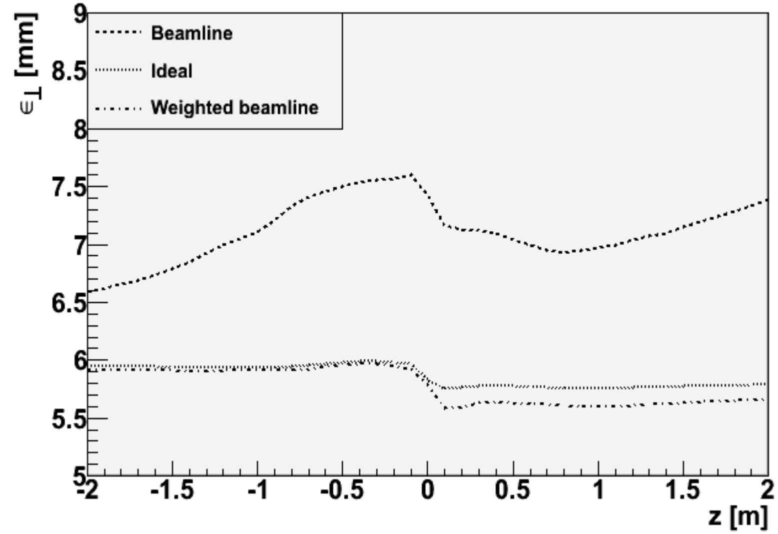


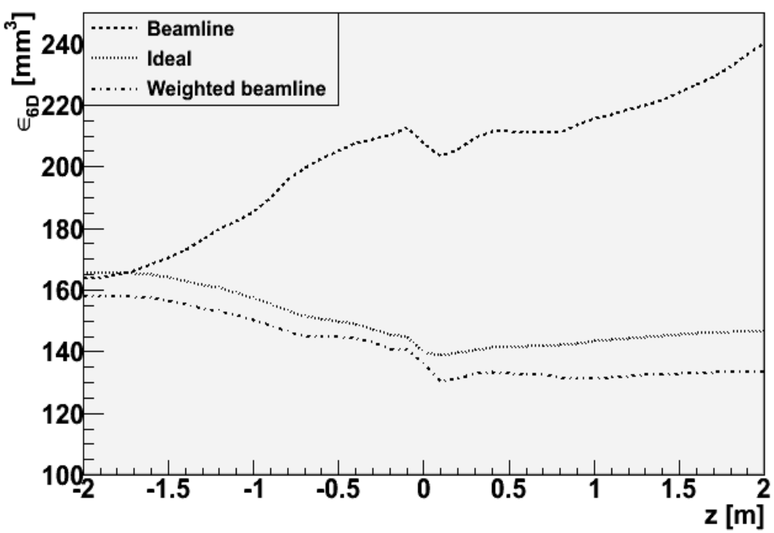
"Standard MICE beam"

- 6 mm transverse emittance
- Large 90 mm longitudinal emittance
  - 25 MeV energy spread
- 200 mm dispersion at the wedge

Realistic Beam and Weighting



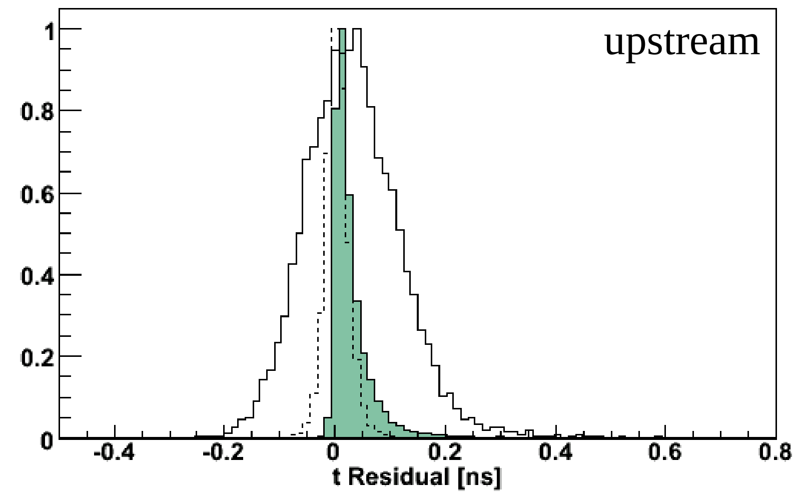


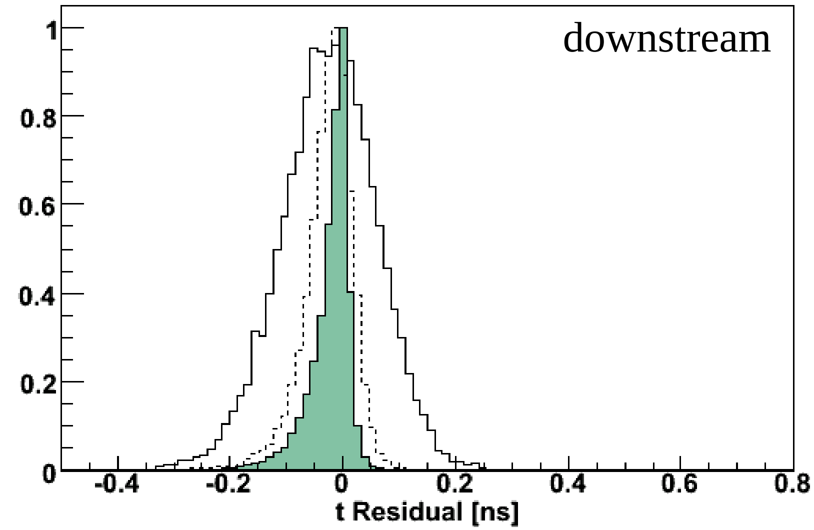


- Emittance change for
  - ideal beam
  - realistic beam (from beamline MC)
  - Realistic beam after weighting
- Note different units etc
- 90 degree plastic wedge

Time Measurement

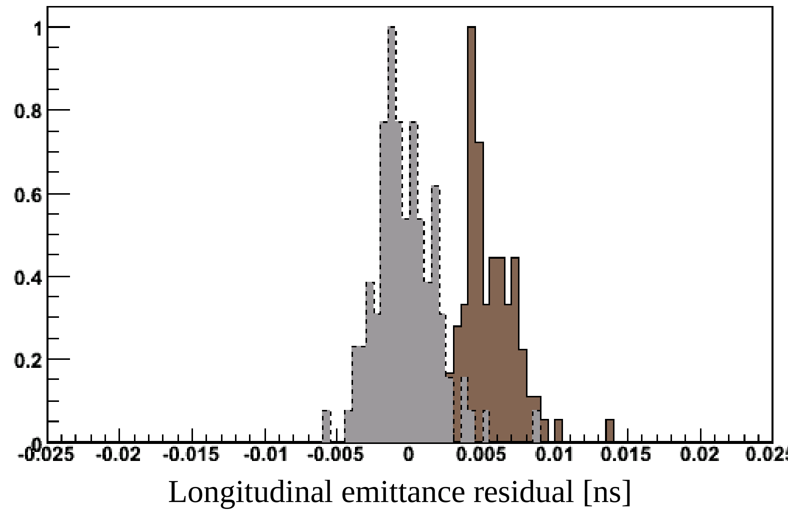
- Time resolution projecting TOF to Tracker Reference Plane
  - ~ 2 m from absorber centre
  - (Filled) energy uncertainty
  - (Dashed) Materials
  - (Full) Both combined with TOF
  - 90 ps RMS upstream
  - 77 ps RMS downstream
- No attempt to use TOF to measure energy
- Compare with beam time spread ~ 1 ns

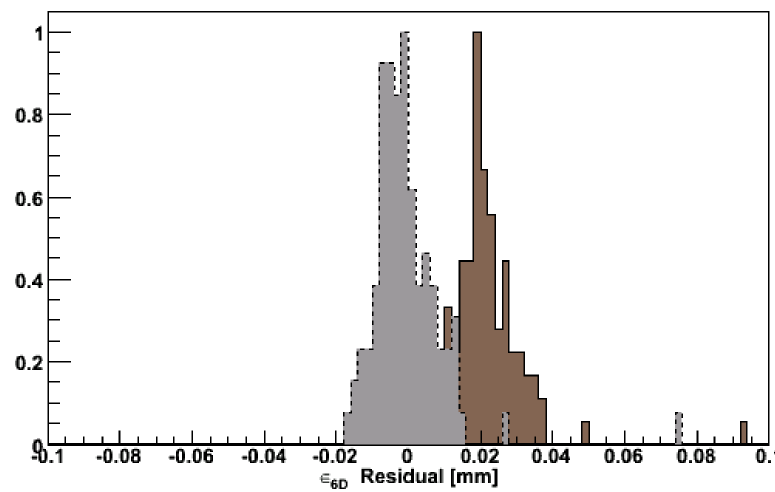




Emittance Measurement

- Longitudinal emittance *convolution systematic* around 0.6 mm
  - 30 mm emittance longitudinal
  - 8 mm beta longitudinal
  - May be reducible by careful analysis
- 6D emittance *convolution systematic* around 0.02 mm
  - (Calculated without dispersion)
  - 6D emittance 10 mm
    - (long 30 mm, transverse 6 mm)
    - Canonical transverse beam
- Detectors are good enough





Evolution of emittance

$$\frac{d\epsilon_x}{dz} = (1 - g_{//})\delta_p \epsilon_x + \chi_x \quad (1)$$

$$\frac{d\epsilon_y}{dz} = \delta_p \epsilon_y + \chi_y \quad (2)$$

$$\frac{d\epsilon_{//}}{dz} = g_{//}\delta_p \epsilon_{//} + \chi_{//}, \quad (3)$$

where δ_p is the fractional change in momentum per unit length, $1/p\ dp/dz$ and χ_x, χ_y and χ_t are excitation terms given by

$$\chi_x = \frac{D_x^2}{2\beta_\perp}\frac{d\delta_{RMS}^2}{dz} + \frac{\beta_\perp}{2}\frac{d\theta_{RMS}^2}{dz} \quad (4)$$

$$\chi_y = \frac{\beta_\perp}{2}\frac{d\theta_{RMS}^2}{dz} \quad (5)$$

$$\chi_{//} = \frac{\beta_{//}}{2}\frac{d\delta_{RMS}^2}{dz} + \frac{D_x^2}{2\beta_{//}}\frac{d\theta_{RMS}^2}{dz}. \quad (6)$$

Here $\beta_\perp$ is the transverse Twiss function, $\beta_{//}$ is the longitudinal Twiss function, $d\theta_{RMS}^2/dz$ is the RMS multiple Coulomb scatter, $d\delta_{RMS}^2/dz$ is the RMS energy straggling and D_x is the dispersion, assumed to be aligned with the wedge. $g_{//}$ is a damping term given by

$$g_{//} = 1 - \frac{D_x}{\rho_0}\frac{d\rho}{dx} \quad (7)$$

Parameter Space

- Explore parameter space to validate theory
- D_x
  - Sample different dispersions
- $\varepsilon_{//}$, $\beta_{//}$
  - Sample different longitudinal phase space
- ρ, $d\rho/dx$
  - Requires different absorbers → probably cannot vary
- ε_x, ε_y
  - Sample different emittances
- β_x, β_y
  - Different optics required
- P_z
  - Different optics required
- Can systematics be reduced by exploring the parameter space?

Absorber Systematics

- What are the systematics from the absorber?
  - What data is required to minimise systematics?
- On-axis thickness
  - Measure thickness to ~ 100 micron (out of 60.5 mm)
  - 0.16 % error in dp/p → O(0.16) % error in emittance reduction
  - Can constrain by looking at dE/dz for low emittance particles
- Opening angle, density
  - Measure t, h to ~ 100 micron
  - Gives larger uncertainty in d/dx(dE/dz) near to the thin end of the wedge
  - Probably reasonable to take the uncertainty at the wedge centre, i.e. O(0.16%)
  - At worst, O(0.16%) uncertainty in $g_{//}$
  - Measure density of off-cuts
    - Can measure density as a function of t, h
  - Can constrain by looking at dE/dz as a function of transverse position or amplitude
    - Seek to measure larger emittances for this purpose

Field Systematics

- Uncertainty in field affects
  - Propagation of beam centroid to the absorber
  - Propagation of dispersion to the absorber
  - Propagation of beta to the absorber
- Presume field systematics will be handled by an “absorber out” run
  - Expect no additional data required

Required MICE Time

- Change absorber to wedge and back again (8 days)
- Transverse emittance and pz scan @ 420 mm, high statistics
  - 3 emittance settings * 3 momentum settings
  - Standard SC magnet currents
  - 1 hour (100k triggers) per run + 3 hours set up time
  - 1 (12 hour) day
- P_z, Beta function at absorber scan with lower statistics
  - Vary beamline to produce 3 emittance settings and 3 momentum settings, keep SC magnets constant, 10k triggers per run
  - 90 minutes to do all that
  - 120 minutes to change magnet currents
  - 3 SC magnet settings per day + 3 hours set up time
  - 10 beta functions => 3 days
  - 10 pz values => 3 days
- 2 days spare
- 17 days total

Conclusions

- Demonstration of emittance exchange is a valuable contribution to the muon collider R&D
- The MICE beamline can be used to propagate the appropriate dispersive beam through Step IV
  - Needs extensive beam sampling
- A plastic wedge will give more longitudinal emittance reduction than LiH
- The MICE detector systems can make a measurement of emittance exchange
- Provisionally, 17 days of MICE time are required
  - 8 days+support staff for an absorber exchange
  - 9 days+physicists for data taking
  - Needs further Monte Carlo to check