Fermilab

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Wedge experiment at MICE

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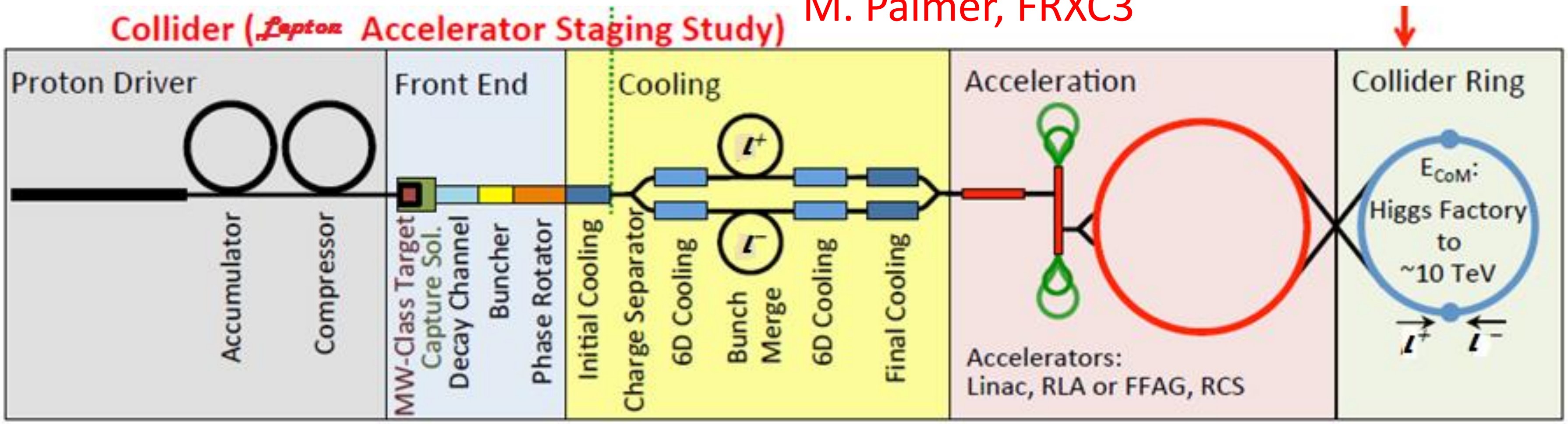
Outline

- Motivation-Final Cooling for a High-Energy Collider
  - small transverse emittances, larger longitudinal emittances
- Final Cooling scenario with wedge exchange
  - w /D. Summers & T. Hart
  - emittance exchange
- MICE – scale model experiment
  - ~10X larger beam, absorber, emittance, …
  - Similar dynamics ~ factor of 4 emittance exchange

Towards multi-TeV lepton colliders

M. Palmer, FRXC3

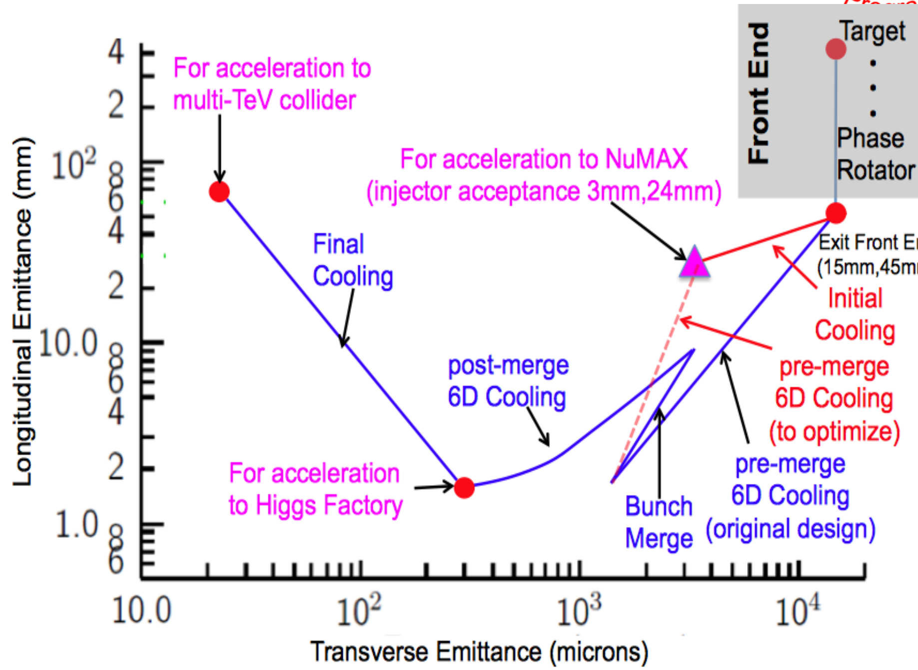


Parameter	Unit	Higgs factory	3 TeV design	6 TeV design
Beam energy	TeV	0.063	1.5	3.0
Number of IPs		1	2	2
Circumference	m	300	2767	6302
β*	cm	2.5	1	1
Tune x/y		5.16/4.56	20.13/22.22	38.23/40.14
Compaction		0.08	-2.88E-4	-1.22E-3
Emittance (Norm.)	mm·mrad	300	**25**	**25**
Momentum spread	%	0.003	0.1	0.1
Bunch length	cm	5	1	1
H. electrons/bunch	10^{12}	2	2	2
Repetition rate	Hz	30	15	15
Average luminosity	10^{34} cm^{-2}s^{-1}	0.005	4.5	7.1

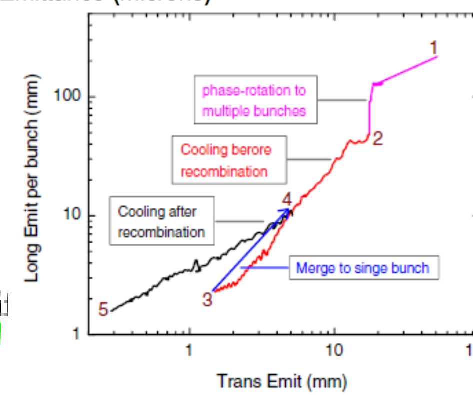
Final cooling baseline

(R. Palmer et al. IPAC12)

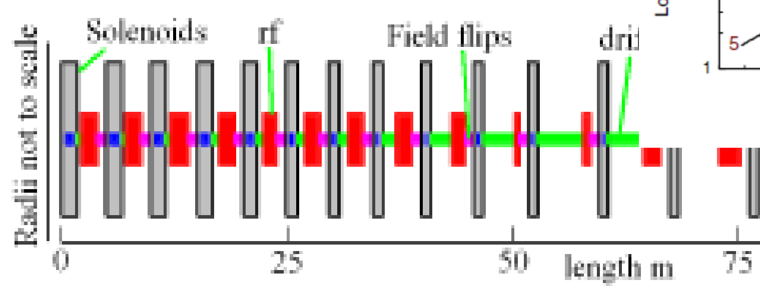
- **Final Cooling**
  - **$\varepsilon_{t,N}$: 3.0 → 0.25 × 10^{-4} m**
  - **ε_L : 1.0→70mm**
    - expensive emittance exchange
- **solenoids, B → 30--50T**
  - **H_2 absorbers,**
  - **Low momentum**



$$\varepsilon_{N,eq} \cong \frac{\beta_t E_s^2}{2\beta m c^2 L_R (dE/ds)}$$



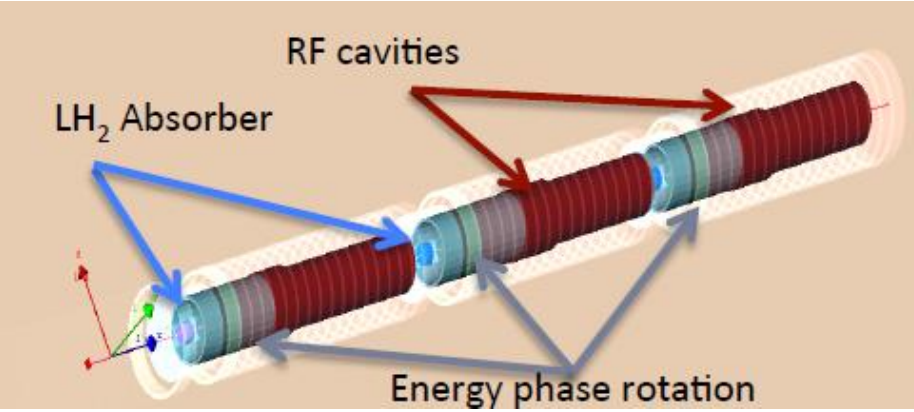
$$\beta_t \cong \frac{2P_\ell\ (GeV/c)}{0.3B}$$

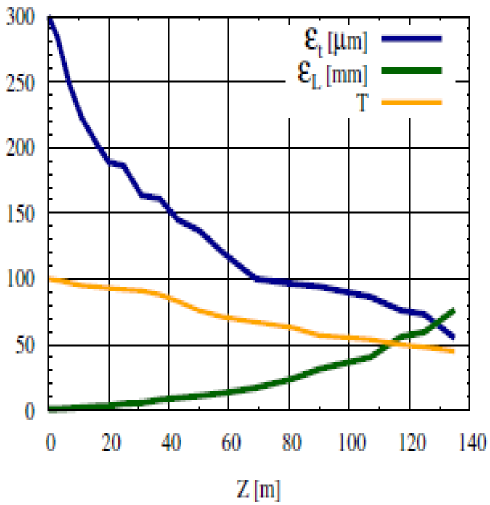


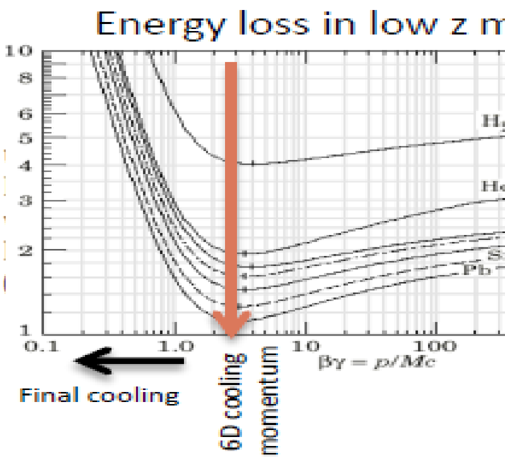
Detailed simulation of final cooling

(H. Sayed et al. IPAC14, PRSTAB 18)

- G4Beamline simulation of final cooling scenario
  - System is ~135m long
  - $\varepsilon_{t,N}$: 3.0 →0.5 10^{-4} m
  - ε_L : 1.0→75mm
    - P_l :135 → 70 MeV/c
    - B: 25 →32 T; 325→ 20MHz
      - not quite specs
  - Transmission ~ 50%
- Predominantly $\varepsilon_{t,N}$ / ε_L emittance exchange
- Use explicit emittance exchange instead?

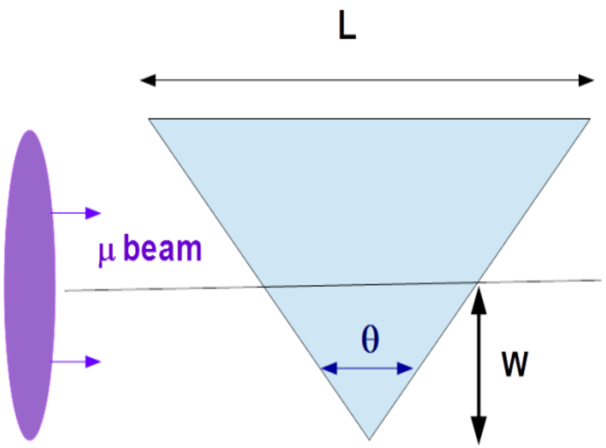






Variant: "thick" wedge emittance exchange

- Use wedge to decrease ε_x
  - By increasing $\delta p/p$
    - increases ε_L, decrease ε_x



- If $\delta p/p$ introduced by wedge >> $\delta p/p_{bea}$
  - can get large emittance exchange
- Example:
  - 100 MeV/c; δp=0.5MeV/c
    - $\varepsilon_\perp = 10^{-4}$m, β_0=1.2cm, Be wedge 0.6cm, 140° wedge
  - obtain factor of ~5 exchange
  - $\varepsilon_x \rightarrow 0.2 \times 10^{-4}$m; δp=2.5 MeV/c
- Much simpler than equivalent final cooling section

"Thick" Wedge theory (MuCool-003)

- Dispersion + wedge is product of two matrices (in x – dp/p)

$$\mathbf{M}_\delta = \begin{bmatrix} 1 & 0 \\ -\delta' & 1 \end{bmatrix} \qquad \mathbf{M}_\eta = \begin{bmatrix} 1 & \eta_0 \\ 0 & 1 \end{bmatrix}$$

- **δ′ = dp/ds 2 tan[*θ* /2]/p**
- variables are [x, δ] , where δ =dp/p
- transport through wedge is transport of [x, δ] phase space ellipse, initially

$$g_0 x^2 + b_0 \delta^2 = \sigma_0 \delta_0$$

- becoming

$$g_1 x^2 + 2a_1 x\delta + b_1 \delta^2 = \sigma_0 \delta_0$$

Results of wedge analysis

- new coefficients

$$b_1 = b_0 + (\eta_0)^2 g_0$$
$$a_1 = \delta' b_0 - \eta_0 (1 - \delta' \eta_0) g_0$$
$$g_1 = \delta'^2 b_0 + (1 - \delta' \eta_0)^2 g_0$$

$$\beta_1 = m_{11}{}^2 \beta_0 + 2 m_{11} m_{12} \alpha_0 + m_{12}{}^2 \gamma_0$$
$$\alpha_1 = -m_{11} m_{21} \beta_0 + (m_{11} m_{22} + m_{12} m_{21}) \alpha_0 - m_{12} m_{22} \gamma_0$$
$$\gamma_1 = m_{21}{}^2 \beta_0 + 2 m_{21} m_{22} \alpha_0 + m_{22}{}^2 \gamma_0$$

- **new δp/p width** ($\varepsilon_{L,1} = \varepsilon_{L,0} (\delta_1/\delta_0)$)

$$\delta_1 = \sqrt{g_1 \sigma_0 \delta_0} = \delta_0 \left[(1 - \eta_0 \delta')^2 + \frac{\delta'^2 \sigma_0{}^2}{\delta_0{}^2} \right]^{1/2}$$

- **new transverse emittance** ($\varepsilon_{x,1} = \varepsilon_{x,0} (\delta_0/\delta_1)$)

$$\varepsilon_{x,1} = \sqrt{g_1 \sigma_0 \delta_0} = \varepsilon_{x,0} \left[(1 - \eta_0 \delta')^2 + \frac{\delta'^2 \sigma_0{}^2}{\delta_0{}^2} \right]^{-1/2}$$

new β_x, η

$$\eta_1 = -\frac{a_1}{g_1} = \frac{\eta_0 (1 - \eta_0 \delta') - \delta' \frac{\sigma_0^2}{\delta_0{}^2}}{(1 - \eta_0 \delta')^2 + \delta'^2 \frac{\sigma_0^2}{\delta_0{}^2}}$$

$$\beta_1 = \beta_0 \left[(1 - \eta_0 \delta')^2 + \frac{\delta'^2 \sigma_0{}^2}{\delta_0{}^2} \right]^{-1/2}$$

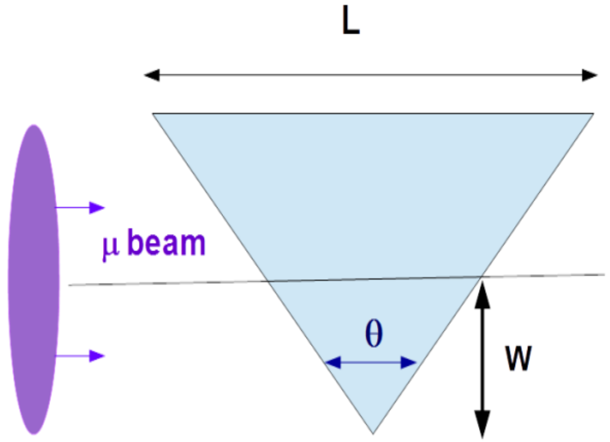
By choosing η_0, δ' (and δ_0, σ_0)

Can decrease ε_x and increase ε_L or vice versa

D. Neuffer

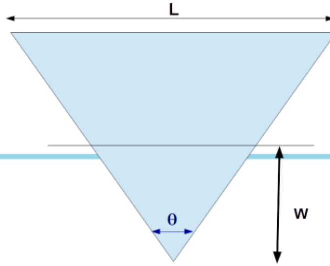
Can get large emittance exchange from single wedges

- Set reference momentum at 100 MeV/c
  - ε_x , ε_y → 10^{-4} m
  - $\beta_x = \beta_y = \sim 1cm$
    - ~1mm beam
    - no initial dispersion η
      - could be improved with matched η
- Need small δp/p
  - δp ~0.5 MeV/c
    - obtain by lengthening and flattening bunch (ε_L = ~0.001m)
- Need dense low-Z wedge
  - Be (ρ=1.86) → Diamond
    - (ρ=3.6 C)
    - dp/ds =15.1 MeV/c /cm
  - B_4C (ρ=2.52) also good



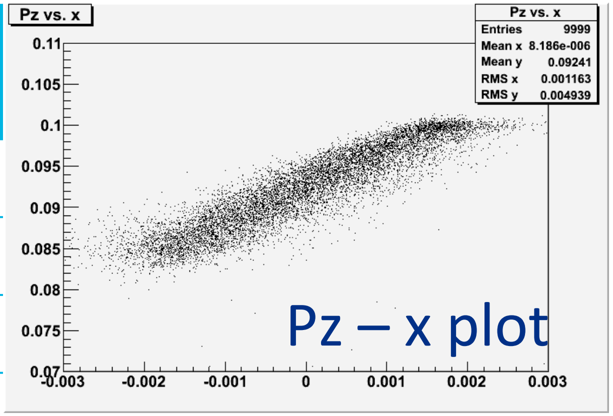
- Evaluate in ICOOL
  - wedge and beam definition, match
  - emitcalc evaluates eigen emittances before/after
  - a few cm transport

Numerical examples



- **Wedge parameters**
  - **Diamond, w=1.75mm, θ = 100° (4.17mm thick at center)**

z(cm)	P_z	$\varepsilon_x(\mu)$	ε_y	ε_L(mm	σ_E MeV	6-D ε increase
0	100	97	95.5	1.27	0.46	1.0
0.4	96.4	33.4	96.3	4.55	1.64	1.24
0.8	92.4	**22.7**	96.5	8.94	3.22	1.65

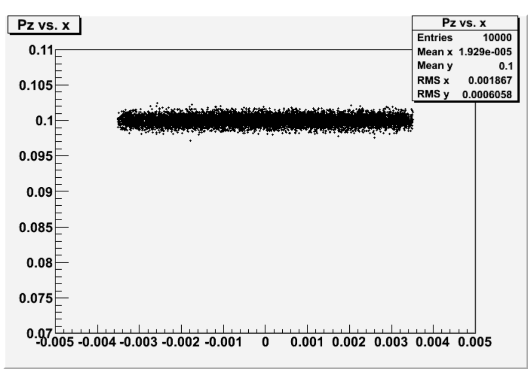


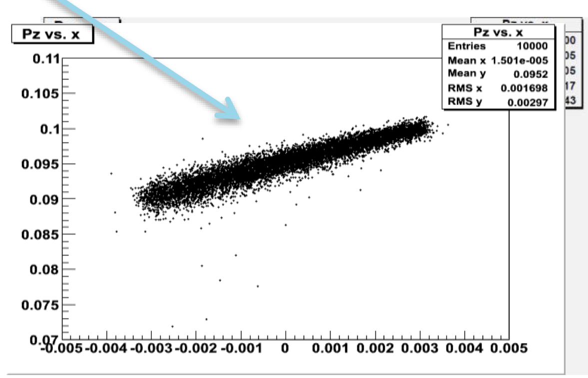
  - **reduces ε_x by factor of 4.3, ε_L increases by factor of 7.0**
    - **first half of wedge more efficient than second half …**
- **Second wedge ?**
  - **if matched to same optics (P_z → 100 MeV/c, σ_E→0.46 MeV)**
    - ε_x : 23 →27μ; ε_y :97 → 23 μ

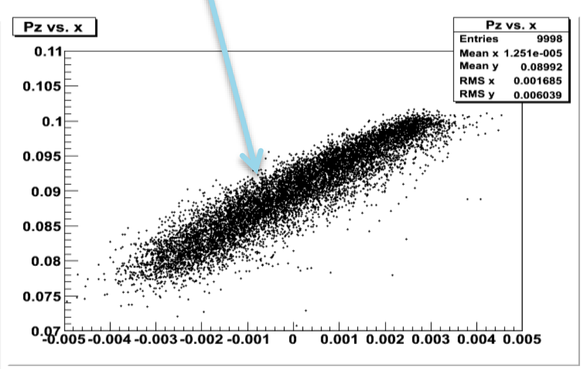
Parameter variations…

- Go to larger initial beams, larger wedge
  - β_t=2.6cm, ε_t =130μ
  - Diamond, w=3.0mm, θ = 85° (5.6mm thick at center)

z(cm)	P_z	ε_x(μ)	ε_y	ε_L (mm)	σ_E MeV	6-D ε increase
0	100	129	127	1.0	0.50	1.0
0.6	95.2	40.4	130	4.03	1.95	1.29
1.2	90.0	**25.0**	127	7.9	3.87	1.54

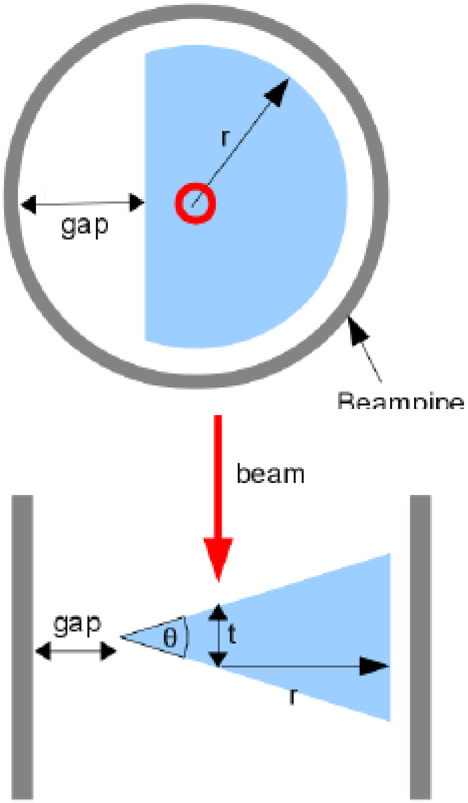






Scale model of final emittance exchange

- Mice 290 **(Rogers, Snopok, Coney, Janssen)** considered adding wedges within the focus coil to explore emittance exchange
  - LiH, CH_2, Be wedges, 3 angles
- For final exchange scale demo, only need CH_2, 60° wedge
- Use 200 MeV/c beam
  - standard settings, zero η



material	LiH	LiH	LiH	C_2H_4	C_2H_4	C_2H_4	Be	Be	Be
θ [°]	30	60	90	30	60	90	30	60	90
r [mm]	225.0	225.0	225.0	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	40.2	40.2	40.2
h [mm]	365.7	290.3	262.7	337.9	277.4	255.3	300.0	259.8	245.1
l [mm]	98.0	167.6	225.0	90.5	160.2	225.0	80.4	150.0	225.0
d [mm]	0	0	37.7	0	0	25.1	0	0	20.1
mass [kg]	12.16	16.27	17.7	12.4	17.3	19.0	20.5	30.6	34.2

Table 3: Parameters of the wedges described in this note. Dimensions are labelled in Figure 9.

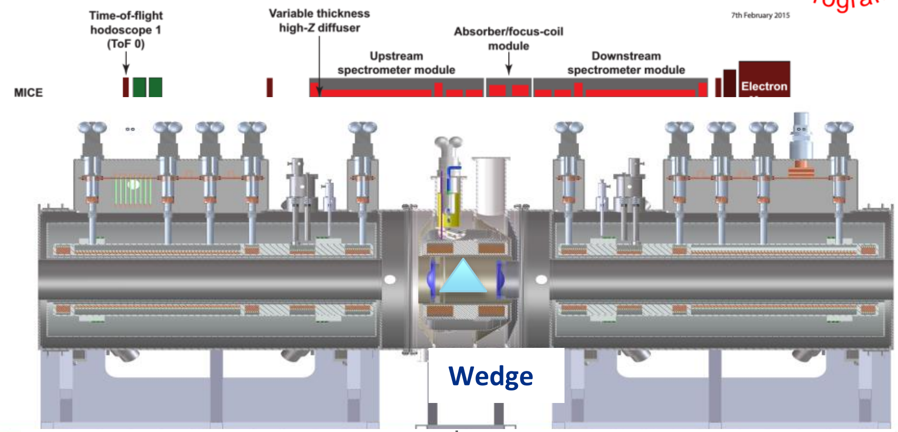
Mice experiment wedges

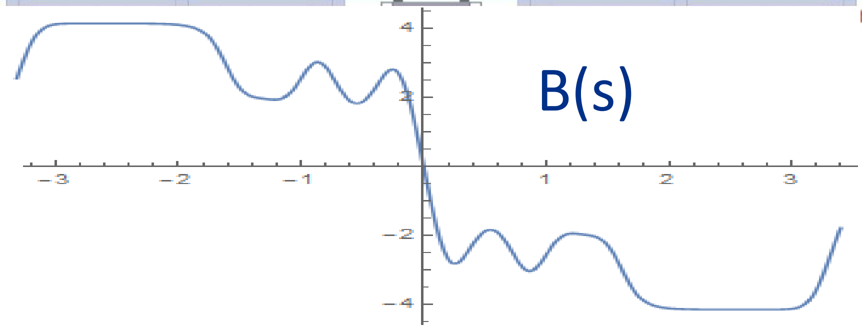
- Step 4 geometry, fields
  - 4.14T solenoids
  - β^{*}= ~0.35m

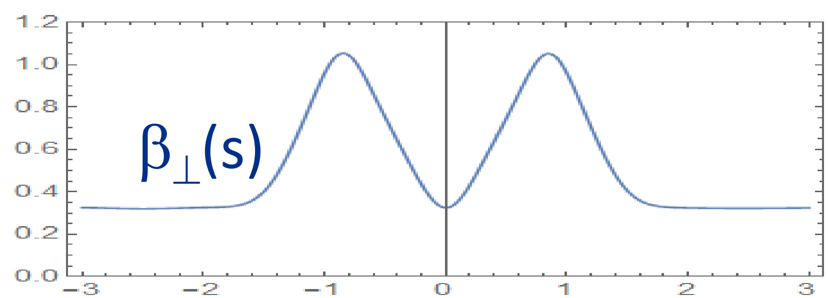
Input Beam:

200MeV/c 0-diffuser setting is best fit:

		p_z (MeV/c)		
		140	200	240
ε_N (π mm · rad)	3	$d = 0.0$ p_{diff}=151 MeV/c α=0.2 β=56 cm	$d = 0.0$ p_{diff}=207 MeV/c α=0.1 β=36 cm	$d = 0.0$ p_{diff}=245 MeV/c α=0.1 β=42 cm
	6	$d = 0.9X_0$ P_{diff}=156 MeV/c α=0.3 β=113 cm	$d = 1.3X_0$ P_{diff}=215 MeV/c α=0.2 β=78 cm	$d = 1.3X_0$ P_{diff}=256 MeV/c α=0.2 β=80 cm
	10	$d = 1.8X_0$ P_{diff}=164 MeV/c α=0.6 β=198 cm	$d = 2.8X_0$ P_{diff}=229 MeV/c α=0.4 β=131 cm	$d = 2.8X_0$ P_{diff}=267 MeV/c α=0.3 β=129 cm



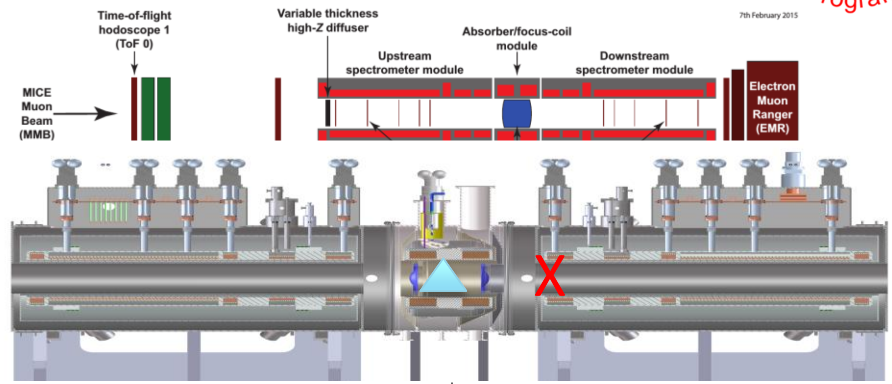


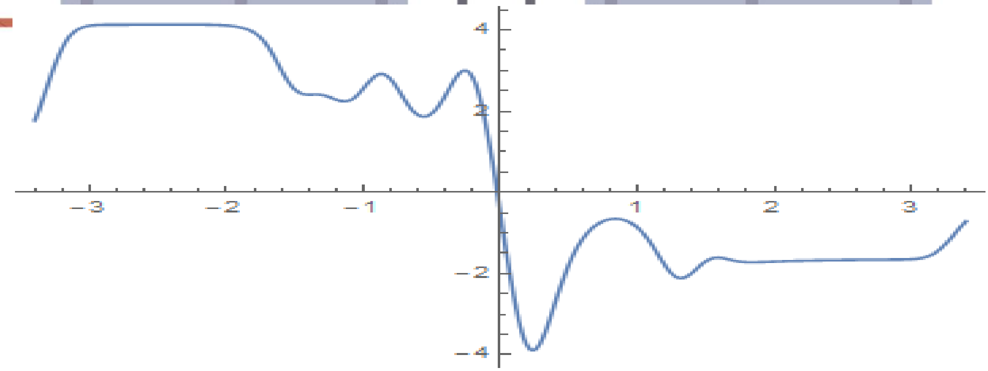


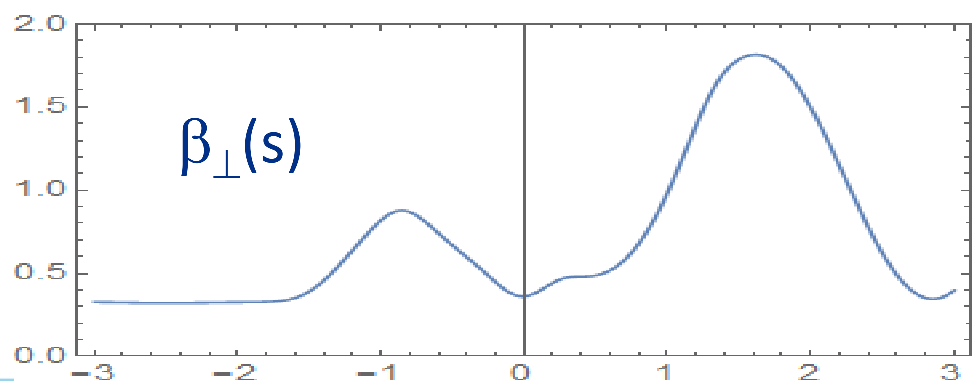
$\varepsilon_{N,rms}$ = ~3 mm-R, select small energy spread for reverse emittance exchange expt.

Mice experiment wedges (step 4-)

- Step 4 geometry,fields
  - 4.14T solenoids
  - β^*= ~0.35m
- With SSD M1 coil off
  - mismatched downstream
  - Keep β^* manageable
    - B → 1.7T
- same lattice into wedge
  - rematch after wedge
  - β_{max} → 1.8m



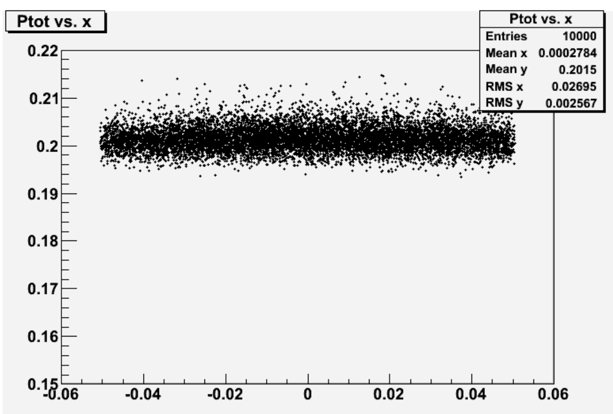


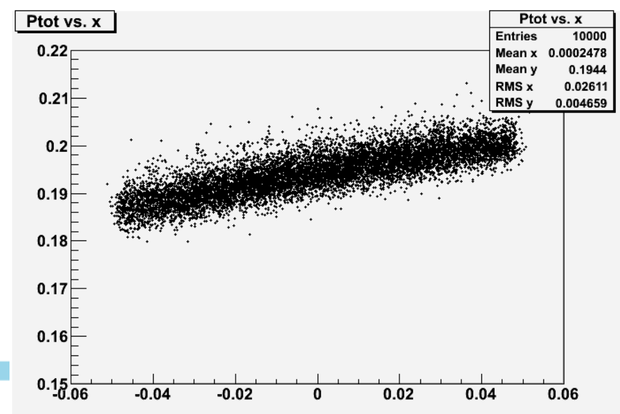


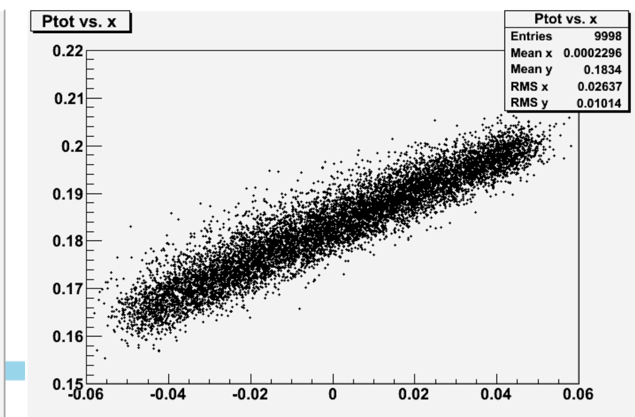
Parameters closer to MICE

- **Wedge at ~MICE parameters**
  - **simplest case: Polyethylene wedge (C_2H_4)**
  - **200 MeV/c beam β_t=36 cm, ε_t =3.04mm**
  - **C_2H_4, w=5cm, θ = 60° (6 cm thick at center)**

z(cm)	P_z MeV/c	ε_x (mm)	ε_y	ε_L (mm)	σ_E MeV	6-D ε increase
0	200	3.04	2.99	2.90	1.82	1.0
6	193	1.44	3.02	6.82	3.86	1.13
12	182	**0.76**	3.00	14.27	8.63	1.23





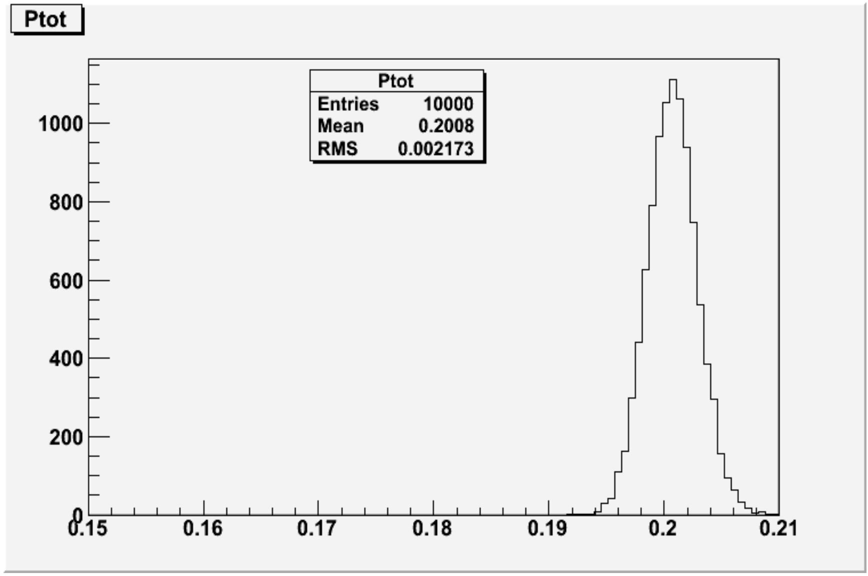


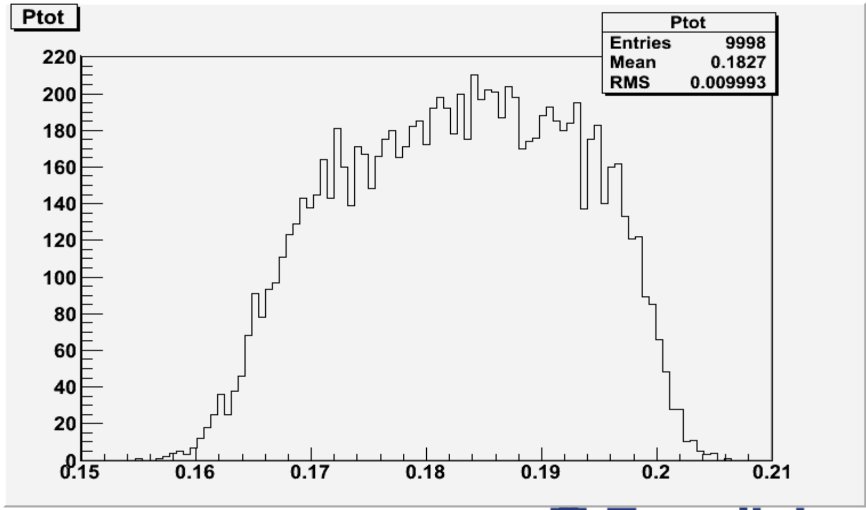
Proof of Principle wedge test

- Simplest verification
  - Does momentum spread increase match calculation?

- Large effect
  - σ_P: 2.0 → 10 MeV/c

- 6-D phase space eigenemittance reconstruction needed to see ε_x reduction
  - $x \rightarrow x + \eta(\delta p/p)$
  - more difficult





Advantages of experiment (Step 4+)

- **Simple hardware**
  - **plastic wedge (not LiH or Be)**
  - **Does not need rf**
  - **step 4 beam configuration**
- **Can we do without SSD M1 ?**
  - **define initial beam in SSU**
    - match to wedge input
    - focus to β^* ~0.3—0.4 m
  - **measure change in δp**
    - agreement establishes **scale model** of final cooling scenario
- **6-D eigen emittance measurement would be better ….with SSD**

Disadvantages

- **Beam comes out of wedge with x-y asymmetry**
  - **β_x = ~0.1m, Dispersion η_x =~0.5m**
    - (β_y =~0.4m, η_y =~0)
- **MICE optics (solenoids) does not match**
  - **6-D emittance measurement of beam may be difficult**
    - canonical eigenemittance calculation?
- **Optics matching (after wedge) is nontrivial**

Summary

- **Thick Wedges could be important part of final cooling scenario**
  - Details depend on optimization and design studies
  - An important part of collider scenario
    - could be part of other particle sources

- Experiment at MICE could demonstrate principle
  - **Large** effect could be demonstrated
    - (unlike baseline cooling demo)
  - variation in input beam selection could also show longitudinal cooling

  - other applications …