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Final Cooling For a High-Luminosity High-Energy Lepton Collider

Super wedgies!

David Neuffer FNAL

Don Summers, T. Hart, … U. Miss.

Outline

- Motivation-**IPAC15**

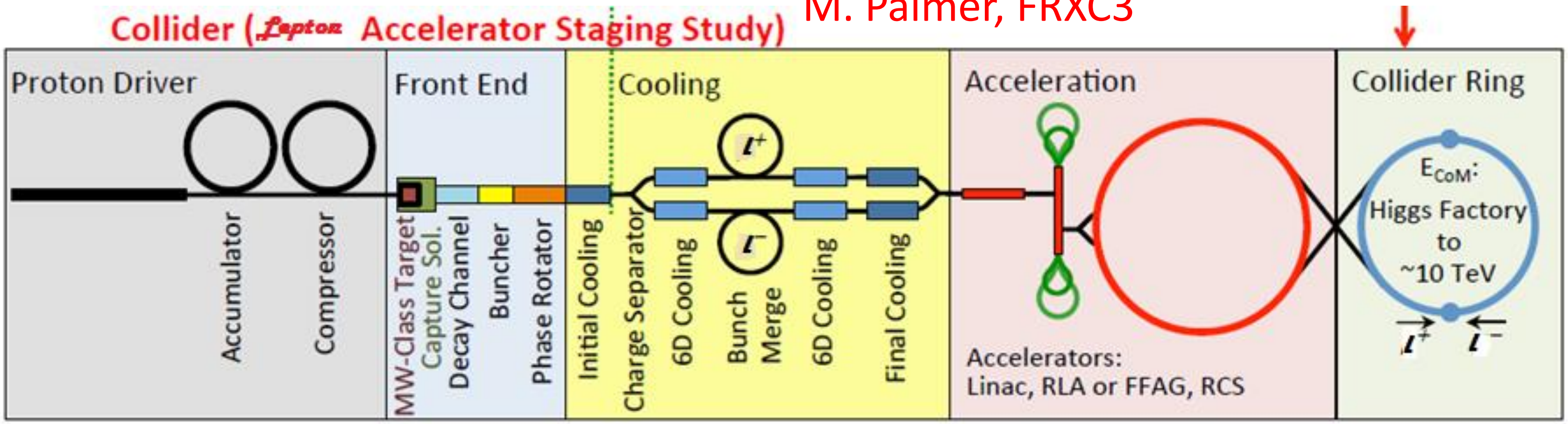
- Final Cooling for a Collider & Simulation
  - R. Palmer & H. Sayed

- Final scenario variations
  - w /D. Summers & T. Hart
  - emittance exchange

Fermilab

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

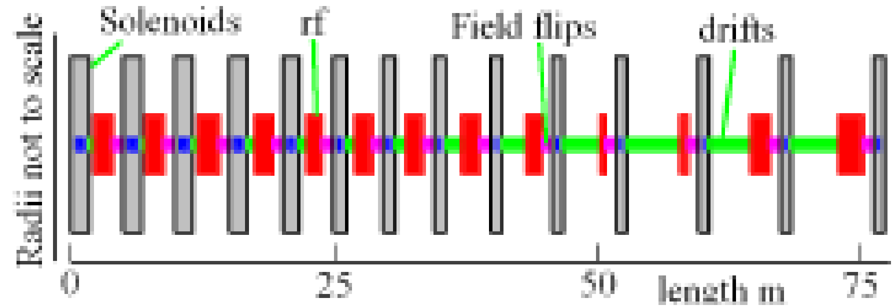
(R. Palmer et al. IPAC12)

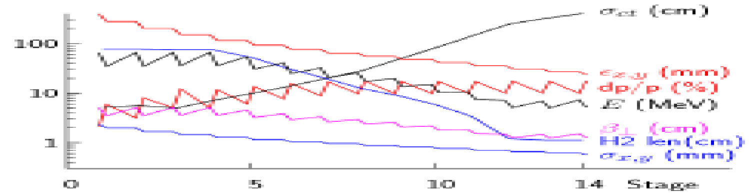
- **Baseline Final Cooling**
  - **solenoids, B → 30--50T**
  - **H_2 absorbers,**
  - **Low momentum**

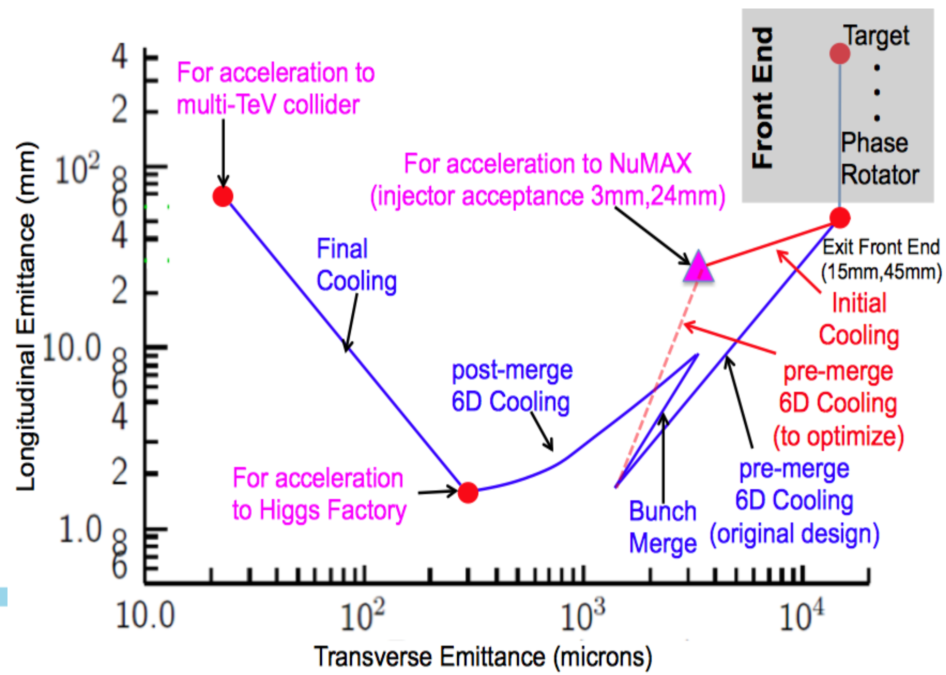
  - **$\varepsilon_{t,N}$: 3.0 →0.3 × 10^{-4} m**
  - **ε_L : 1.0→70mm**
    - expensive emittance exchange

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

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







Detailed simulation of final cooling

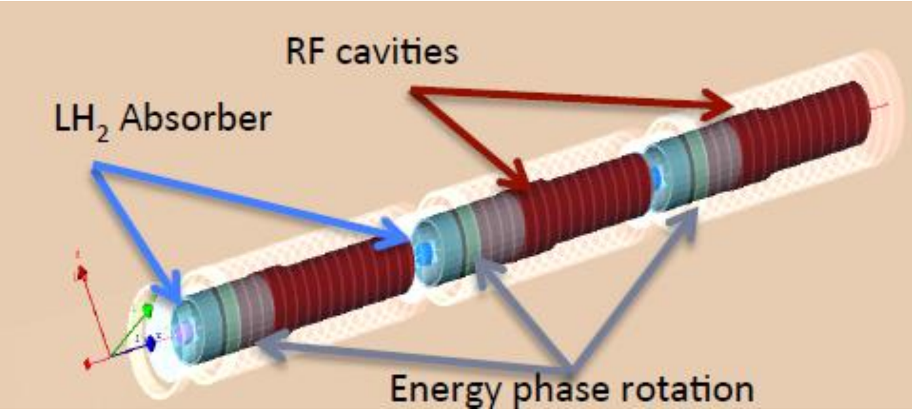
(H. Sayed et al. IPAC14)

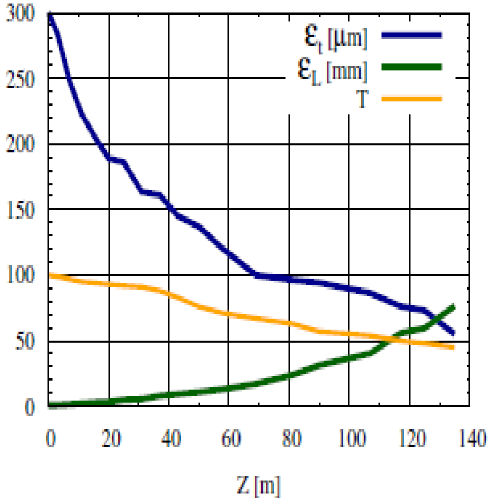
- G4Beamline simulation of final cooling scenario
  - System is ~135m long
  - $\varepsilon_{t,N}$: 3.0 → 0.5 10^{-4} m
  - ε_L : 1.0 → 75mm

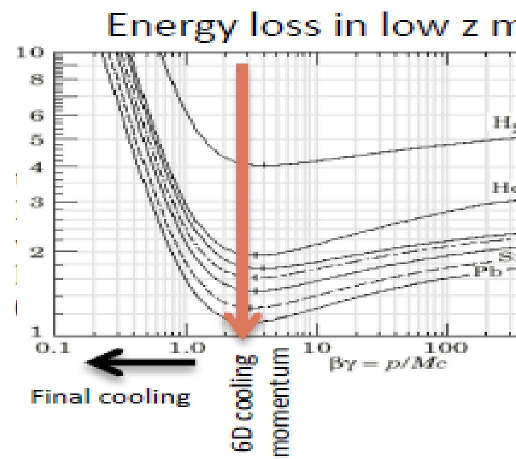
    P_l :135 → 70 MeV/c

    B: 25 → 32 T; 325 → 20MHz

    - not quite specs
  - Transmission ~ 50%







- Predominantly $\varepsilon_{t,N}$ / ε_L emittance exchange

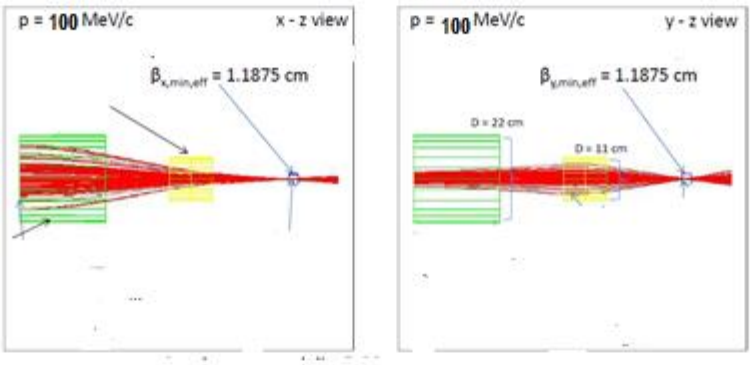
Variant Approaches

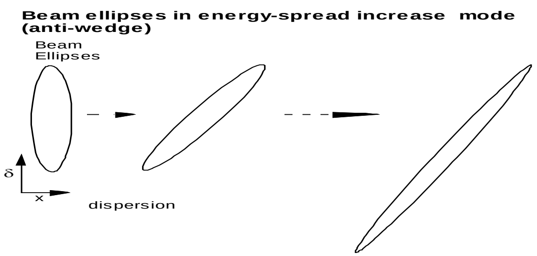
- Keep P_l, B, E′, f_{rf} within ~current technology
  - P > 100MeV/c; B~8➔15T; f_{rf} > ~100MHz
  - round to flat transformation
  - beam slicing and recombination

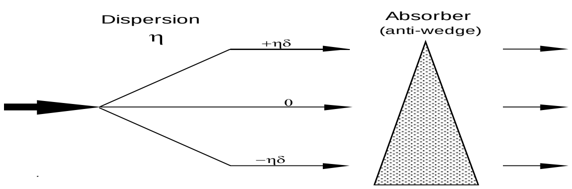
- Explicitly use emittance exchange in final cooling
  - thick wedge energy loss

Variant: "thick" wedge transform

- Use wedge to increase δp/p
  - increase ε_L, decrease ε_x
- If δp/p introduced by wedge >> $\delta p/p_{beam}$;
  - can get large emittance exchange
    - exchanges x with δp (Mucool 003)
      - also in CERN 99-13, p.30
- 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







$$\varepsilon_1 = \varepsilon_0 \left[(1 - \eta_0 \delta')^2 + \frac{\delta'^2 \sigma^2}{\delta_0^{\,2}} \right]^{-1/2}$$

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Fermilab

Wedge theory (MuCool-003)

- Dispersion + wedge is product of two matrices

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

- 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

- **new coefficients**

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

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

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

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

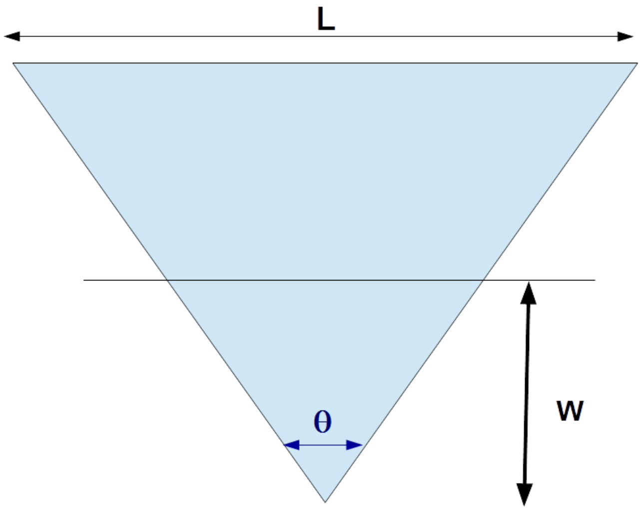
new β_x, η

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

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

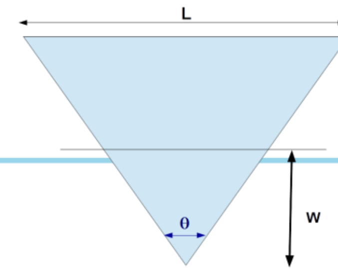
Evaluation of Super-wedge examples

- **Set reference momentum at 100 MeV/c**
  - ε_x , ε_y → 10^{-4} m
  - $\beta_x = \beta_y$ = ~1cm
    - ~1mm beam
      - round numbers …
- **Need small $\delta p/p$**
  - 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



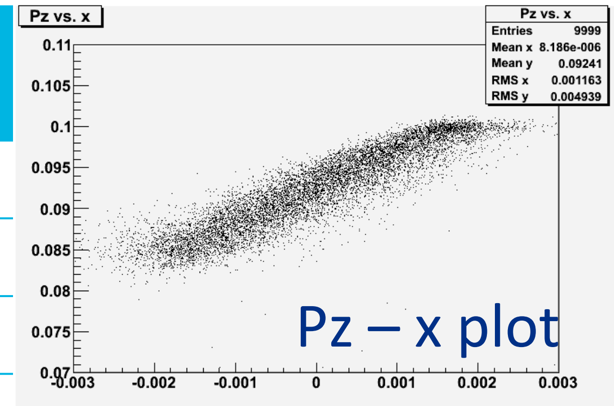
- **Evaluate in ICOOL**
  - **wedge and beam definition, match**
  - **emitcalc evaluates eigen emittances before/after**
  - **a few cm transport**

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



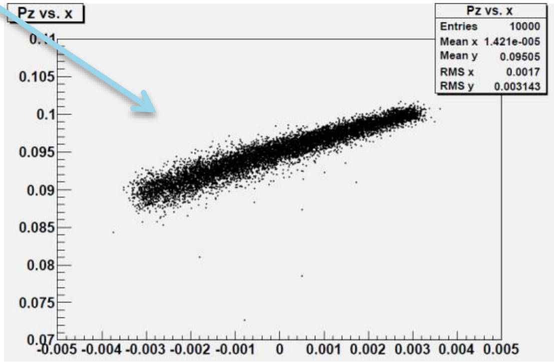
  - **reduces ε_x by factor of 4.3, ε_L increases by factor of 7.0**
    - **first half of wedge more efficient than second half …**
- **Second wedge ?**
  - **if matched to same optics (P_z → 100 MeV/c, σ_E → 0.46 MeV)**
    - ε_x : 23 → 27μ; ε_y :97 → 23 μ

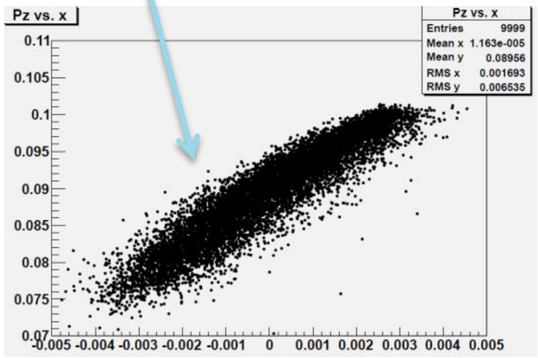
Parameter variations…

- **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	0.91	0.44	1.0
0.55	95	36.6	131	4.33	2.08	1.34
1.1	89.6	**25.0**	132	8.66	4.17	1.845

Pz – x plots





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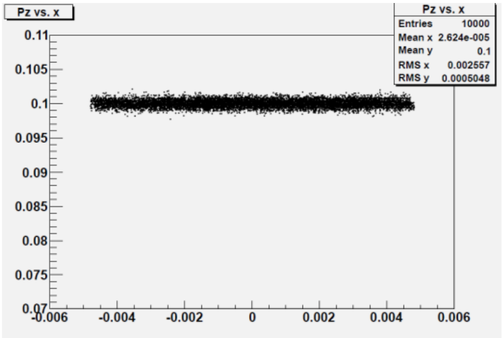
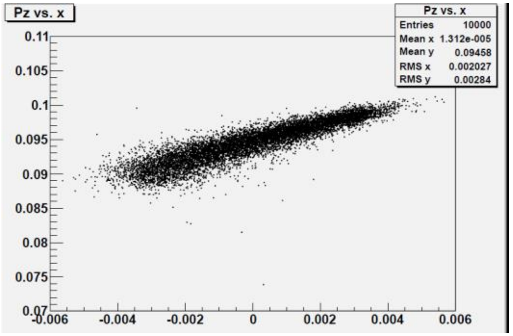
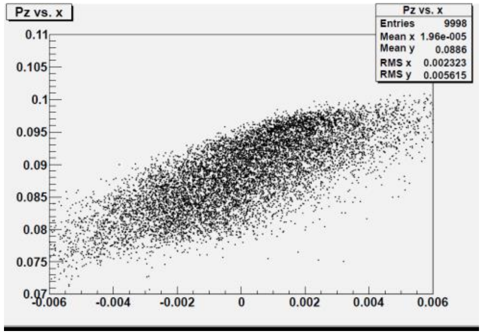
Parameter variations…

- Go to larger initial beams, larger wedge
  - β_t=3.2cm, ε_t =200μ
  - Graphite, w=4.5mm, θ = 100° (9.6mm thick at center)

z(cm)	P_z	ε_x(μ)	ε_y	ε_L (mm)	σ_E MeV	6-D ε increase
0	100	194	191	1.09	0.53	1.0
1.4	94.6	67.3	193	3.9	1.88	1.245
2.8	88.5	**47.3**	192	7.7	3.7	1.72





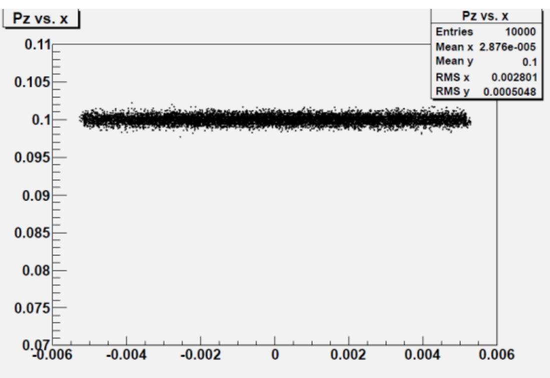


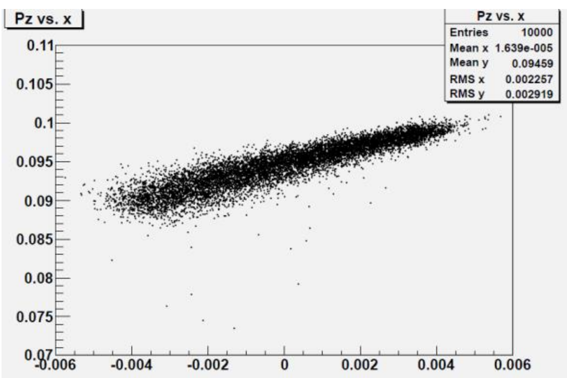
Pz – x plots

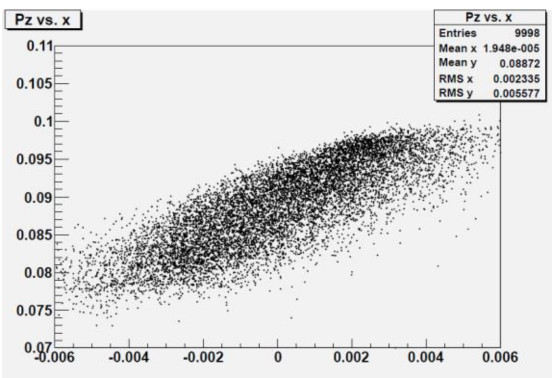
Parameter variations…

- Go to larger initial beams, larger wedge
  - β_t=3.6cm, ε_t =200μ
  - Be, w=5mm, θ = 110° (14.3 mm thick at center)

z(cm)	P_z	ε_x(μ)	ε_y	ε_L (mm)	σ_E MeV	6-D ε increase
0	100	194	191	0.99	0.53	1.0
1.4	94.6	60.2	191	4.0	1.88	1.24
2.8	88.7	**43.8**	189	7.5	3.7	1.69







Compare with current final scenario

- last 120 m

  14 30 T SOLENOIDS

  ~**1GeV rf**

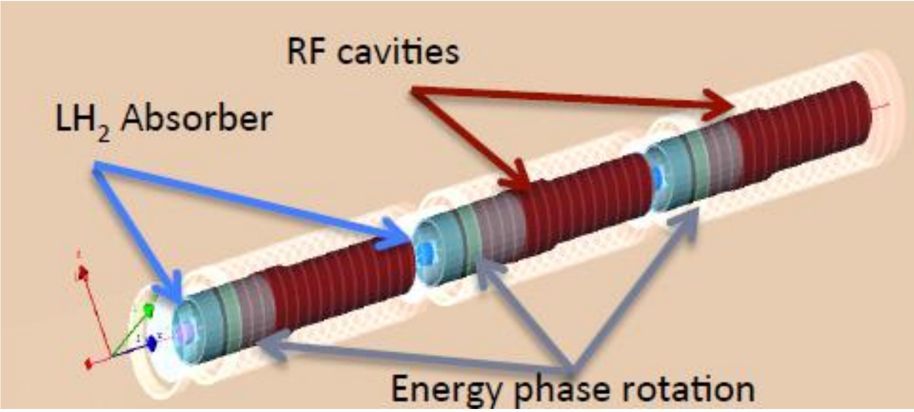
  – $\varepsilon_{t,N}$: 180 → 55 10^{-6} m
  – ε_{L} : 2.0 → 75mm

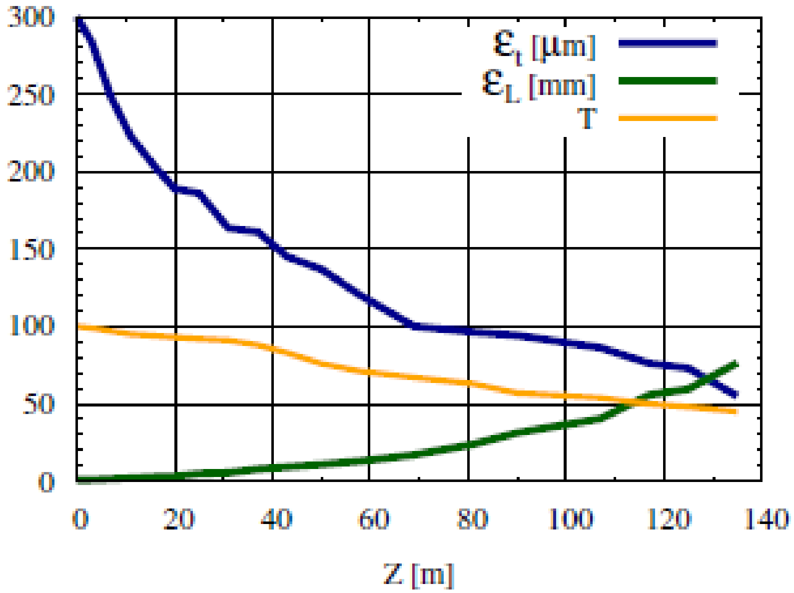
  B: **25 → 32** T; 325 → 20MHz

    - not quite specs

  – **Transmission ~ 50%**

- Two Be wedges ~ 3cm
  – $\varepsilon_{t,N}$: 200 → 40 10^{-6} m
  – ε_{L} : 1 → 50mm
  – **Transmission ~ 95+%**
    - ~30 MeV rf

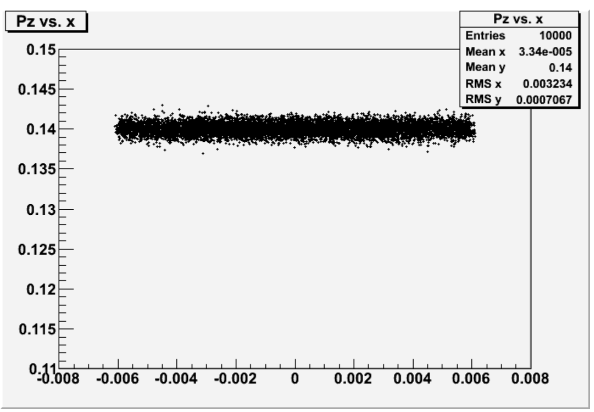


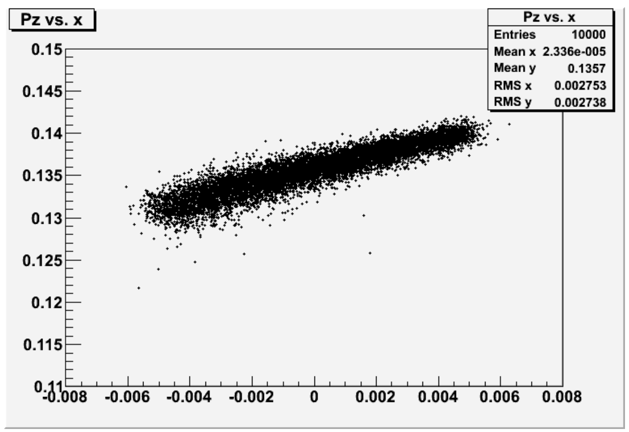


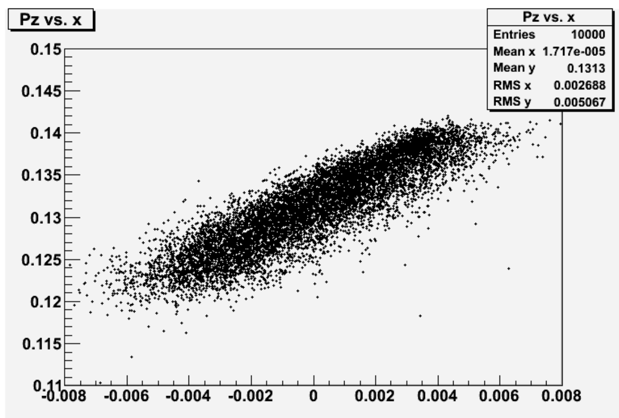
Parameters closer to MICE

- Go to larger initial beams, larger wedge, higher P
  - β_t=5cm, ε_t =272μ
  - C, w=5mm, θ = 105° (14.3 mm thick at center)

z(cm)	P_z MeV/c	ε_x(μ)	ε_y	ε_L (mm)	σ_E MeV	6-D ε increase
0	140	272	268	1.22	0.68	1.0
1.4	135.7	102	273	4.0	2.15	1.2
2.8	131.3	**67.8**	275	7.5	3.92	1.44







Need to complete scenario

- **Match into first wedge**
  - **long ~0.15m, δp = 0.5MeV/c**
  - **β_t ~ 3cm ε_t ~ 200μ**
    - beam out has dispersion η~4cm, δp ~3 MeV/c, β_x ~0.5cm
- **Match into second wedge**
  - **Accelerate centroid to 100(?) MeV/c**
  - **long ~1m, δp = 0.5MeV/c**
  - **β_t ~ 3cm ε_1 ~ 200μ, ε_2 ~ 40μ**
  - **Dispersion match to ~0**

- **Biggest problem could be optical match out of wedge**
  - Beam has small x-emittance
  - dispersion + smaller β_x
  - larger **δp**
- **Similar to PIC match?**

Disadvantages

- exchange per wedge limited to ~4-6 x (?)

- Does not cool
  - beam heating by >~25%; more for larger exchange

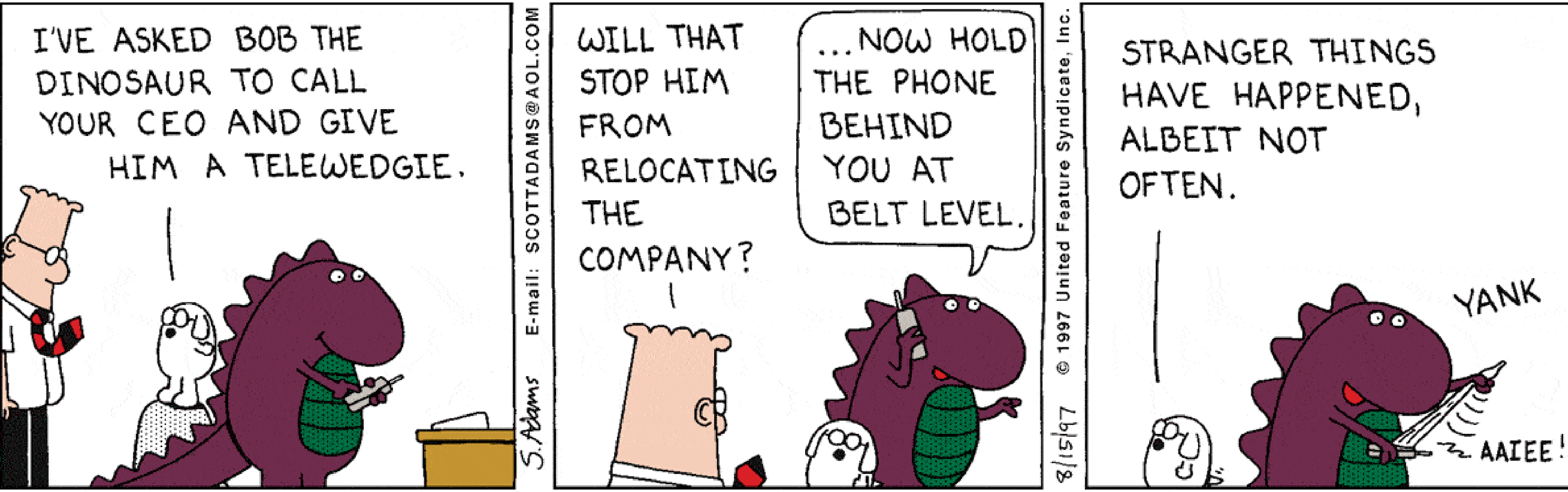
- Optics matching is nontrivial

Summary

- **Thick Wedge parameters are so attractive it has to be part of final cooling scenario**
  - Details depend on actual implementation values and matching solutions
  - how many passes possible 2→3→4 ?
  - how much longitudinal emittance increase is tolerable?
- Not optimized (100MeV/c → ???)

- Could we do an experiment at MICE ??
  - cm-scale dense large-angle wedge, small δE initial beam

Telewedgie…



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YANK
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