“Final Cooling” R&D requirements

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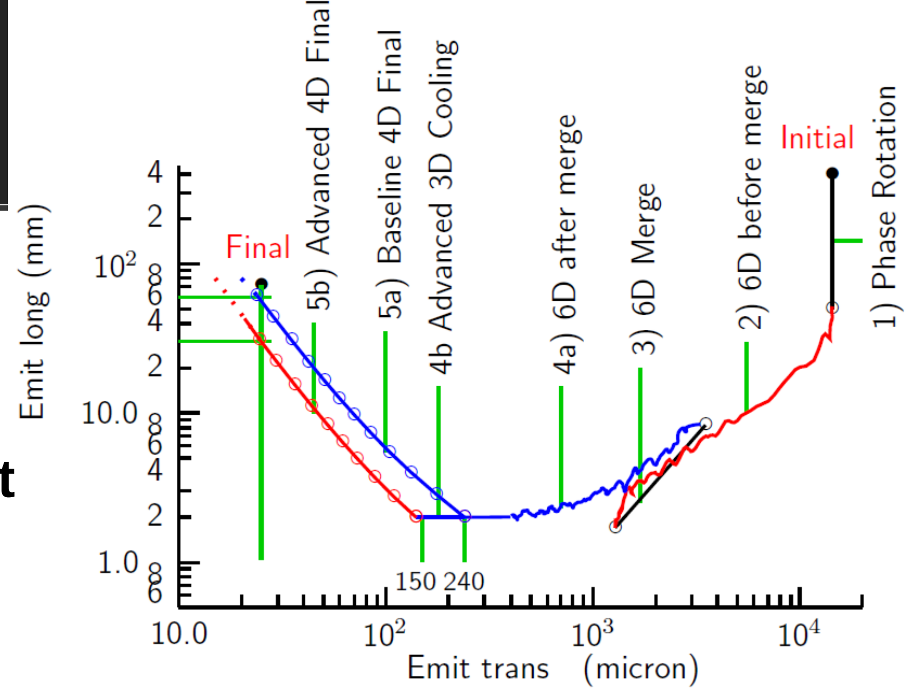
Fermilab

Introduction

- "final cooling" ≅ any thing we add after baseline 6-D cooling channel to improve luminosity
  - Open ended research possibilities
- MAP baseline – high field $B_{z,}$ low-E μ, low-f RF
  - Needs extensive study
- Other possibilities
  - Wedge emittance exchange
  - Li lens, plasma lens
  - PIC cooling
  - slice (x,y) and recombine (z-dE)
  - New ideans

Baseline Cooling

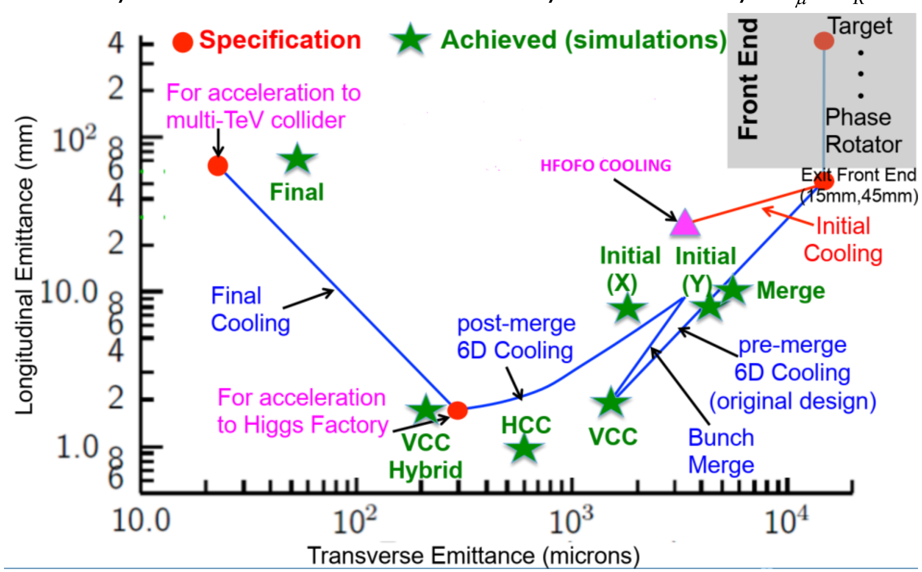
- **For high-energy collider, we want transverse emittance as small as possible**
- **Ionization cooling equations get you to ε_t = 0.0002 m (1984)**



$$\varepsilon_{N,eq} \cong \frac{\beta_t E_s^2}{2\beta m c^2 L_R (dE/ds)} \qquad \beta_t \cong \frac{2P_\mu \ (GeV/c)}{0.3B}$$

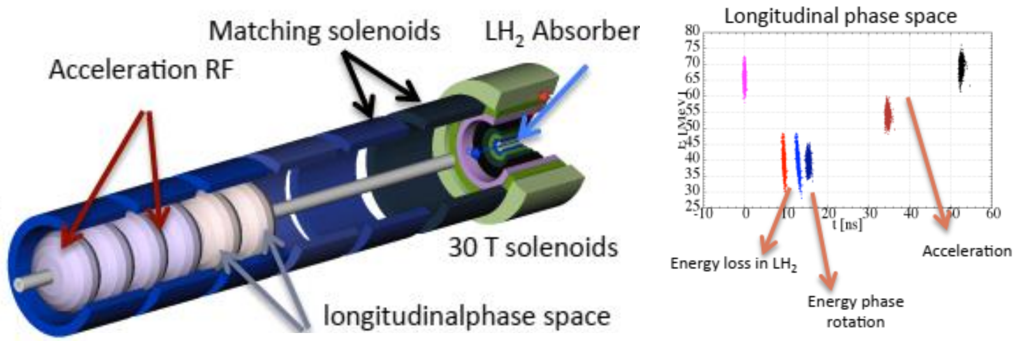
$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta\gamma\ \beta_\perp}{2}\frac{d\left\langle \theta_{rms}^{\ 2}\right\rangle}{ds} = -\frac{g_\perp}{\beta^2 E}\frac{dE}{ds}\varepsilon_N + \frac{\beta_\perp E_s^2}{2\beta^3 m_\mu c^2 L_R E}$$

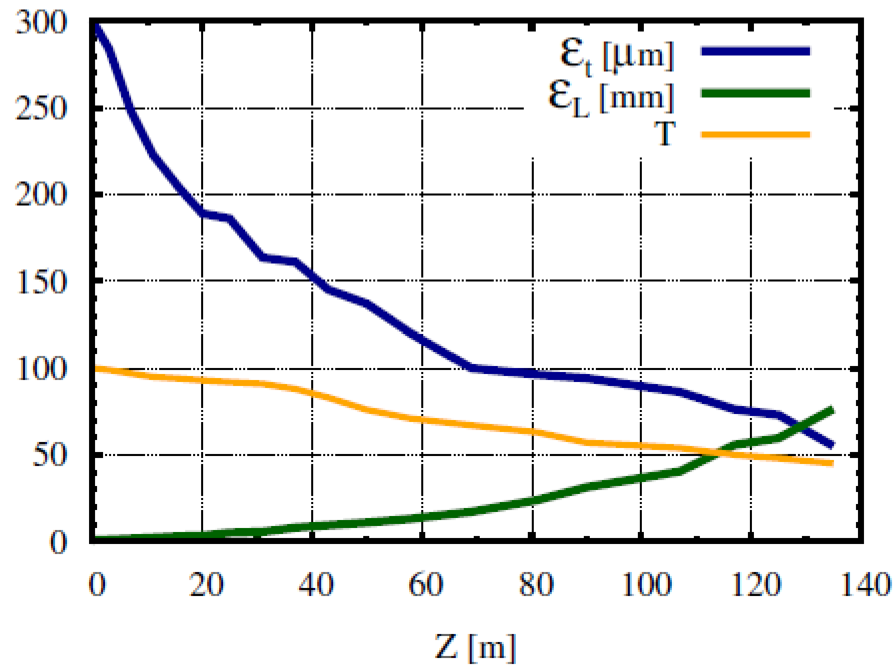
- **Minimize ε_t by large B, small P_μ**
  - B→ 30T +
  - P→ <100MeV/c
  - LH_{2+} absorber



MAP Final Cooling
R. Palmer, H. Sayed et al.

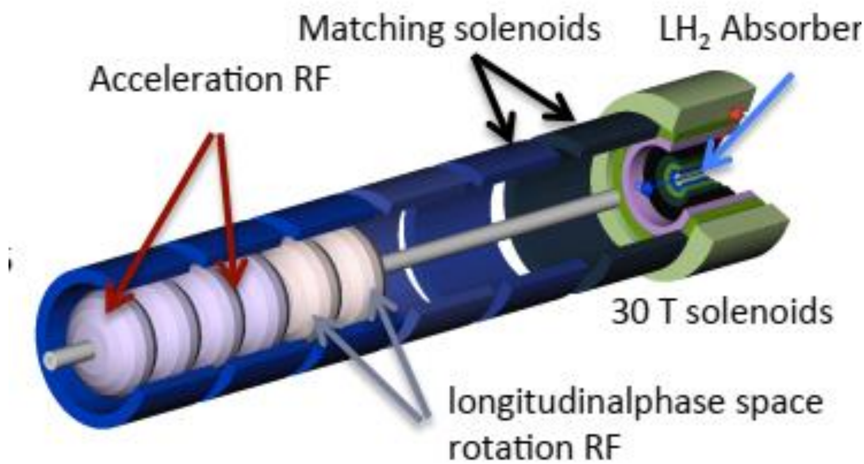
- **135m long**
- **Consists of 16 stages**
  - –130→110→90→70 MeV/c
    - 62 MeV → 21 MeV
  - –B: 25→30 T
  - –Rf: 325 → 10 MHz
    - Some field flips
- **But**
  - – Does not quit meet goals
  - – Losses are too large
    - Needs improvement





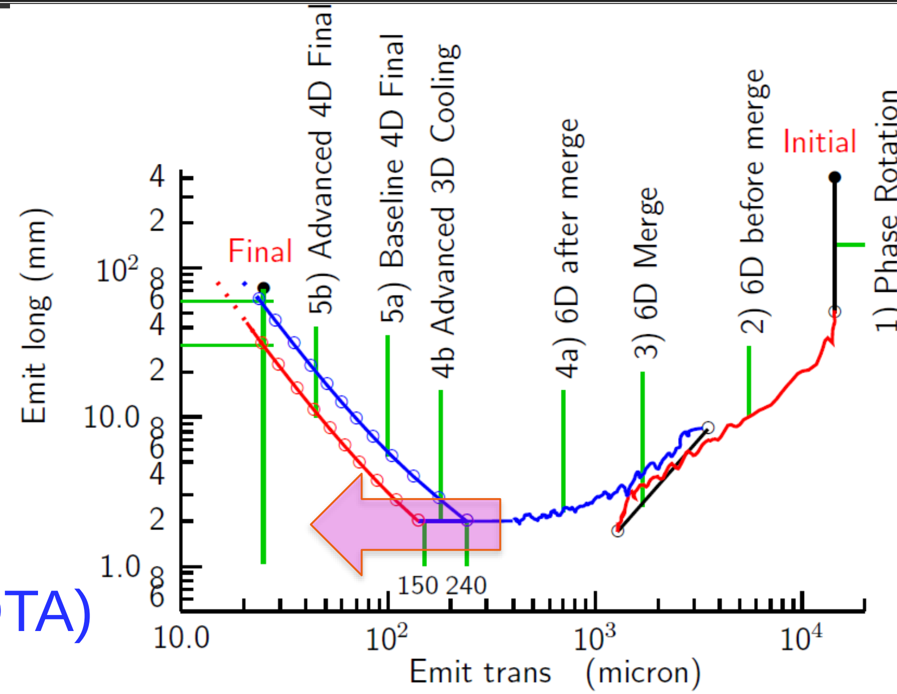
Effort needed

- **Simulation/design needed**
  - 2 FTE/ yr ?
  - Verify/improve/replace MAP
- **Engineering needed**
  - Complete design of at least one segment
- **Prototypes**
  - Solenoid 30 T→ ?
  - RF segment ?



Extend Cooling with Advanced Methods…

- **Parametric resonance IC**
  - Derbenev, Morozov
- **Use Li lens for cooling**
  - $\varepsilon_{t,N} \rightarrow <0.0001$m
- **Plasma lenses**
- **Optical stochastic cooling**
  - First demonstration (2021, IOTA)
- **Extend to higher B fields**
  - RFOFO-D. Summers, T. Hart
- **Phase space manipulations**
  - Slice x and/or y, drift, recombine,
- **Emittance Exchange**
  - wedges

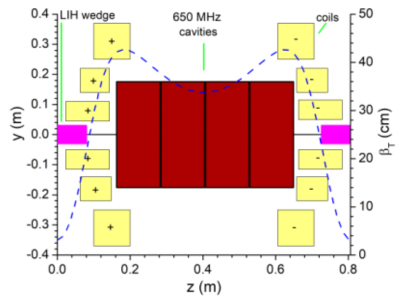


Requires X? FTE for studies

Engineering, demonstrations?

Extend Rectilinear channel with large B –D. Summers, T. Hart (2021)

- **Extend Rectilinear channel with 21T, 28, 35, 42 T**



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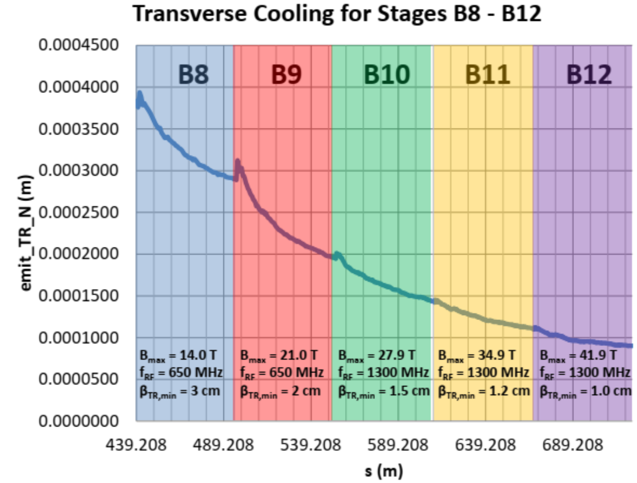
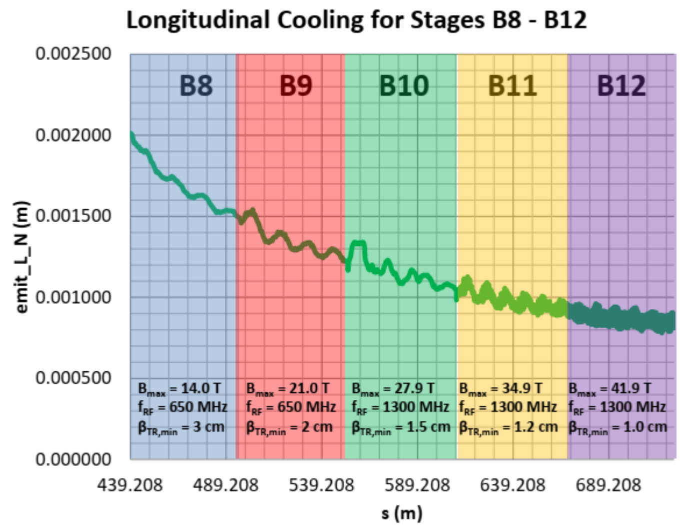
- **$\varepsilon_t \rightarrow$ 0.0001 m, $\varepsilon_L \rightarrow$ 0.0008 m**
- **Cooler beam into "Final Cooler"**



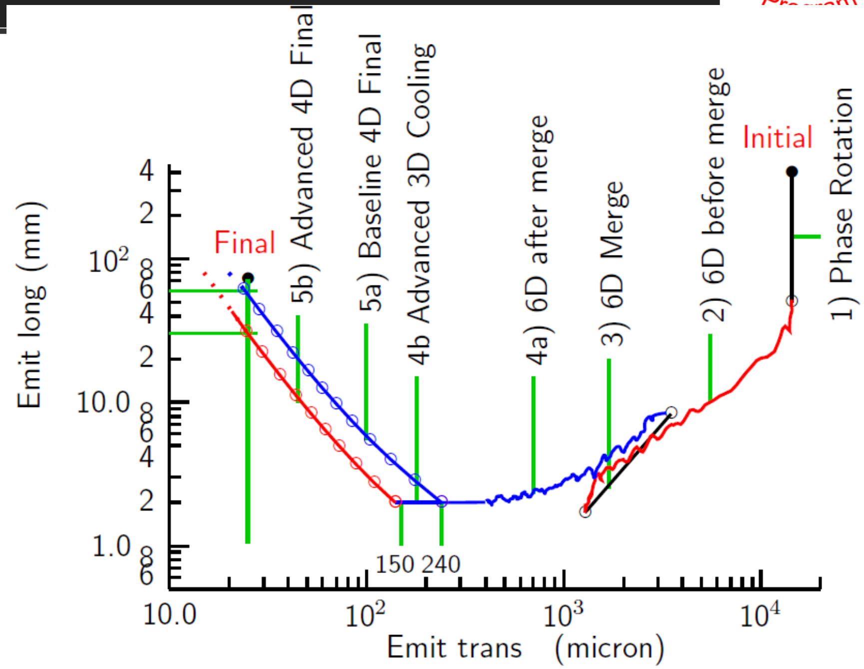


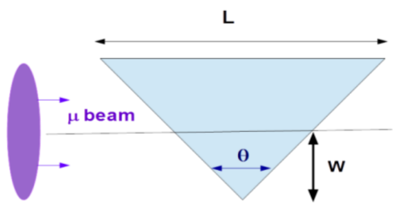
Wedges for Final Cooling

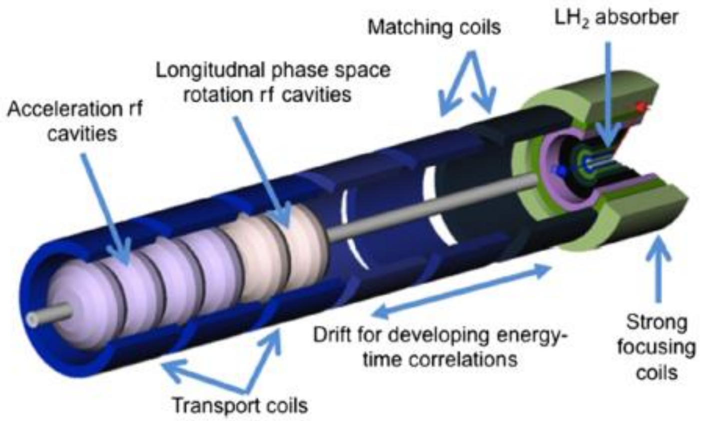
- TeV Collider wants small ε
  - ε → 25 μm or less
- Baseline final cooling is low…..

  Mostly emittance exchange

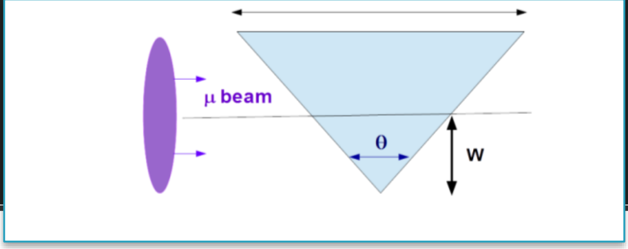
  Consider
- Can do much of this with wedge absorbers …





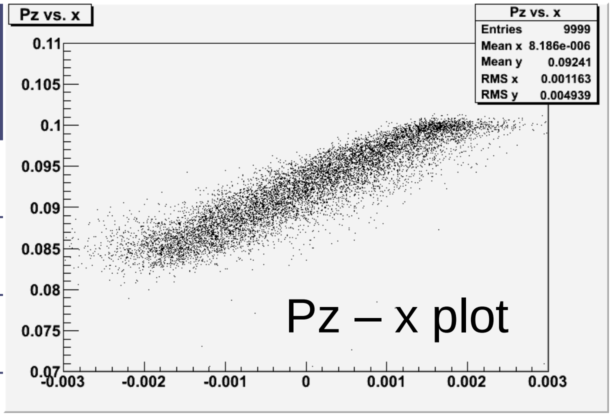


Numerical example



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

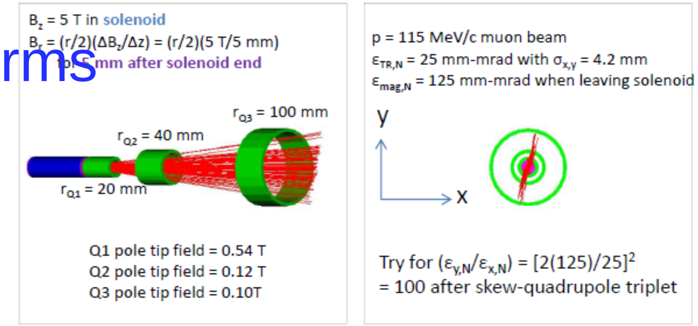
z(cm)	P_z	$\varepsilon_x(\mu)$	ε_y	ε_L(mm	σ_E MeV	6-D ε increase
0	100	97	95.5	1.27	0.46	1.0
0.4	96.4	33.4	96.3	4.55	1.64	1.24
0.8	92.4	**22.7**	96.5	8.94	3.22	1.65



  - 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 rematched to same optics (P_z → 100 MeV/c, σ_E→0.46 MeV)
    - ε_x : 23 →27μ; ε_y :97 → 23 μ

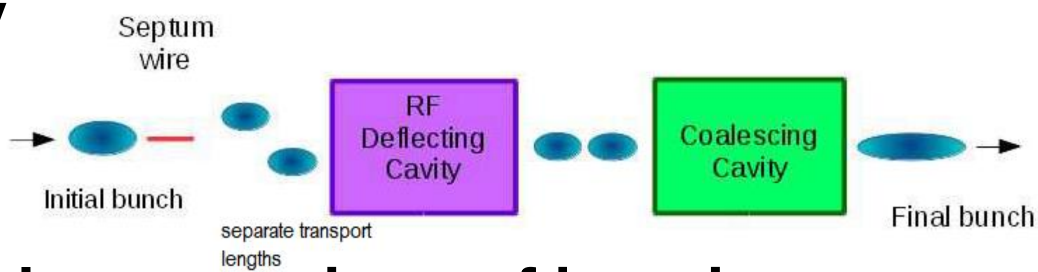
Wedge R&D

- **Reduced emittance requires optical matching**
  - X-amplitude becomes dispersion
  - Dispersion, β-functions + longitudinal
    - Quads, dipoles and solenoids
  - **Part of general problem of optical transport at low energy**
    - Mixing Quad, solenoid focusing
  - Include Round to Flat beam transforms
    - ~3 skew quads : ε_+, ε_- → ε_x, ε_y
- **1-2 FTE ??**
- **Demonstration ?**
  - ?100 MeV/c μ- beam, optics to demonstrate matching
    - Could be affordable …



Emittance exchange: Slice and dice

- **Slice beam transversely**
- **Drift separated beams**
- **Combine longitudinally**



Two-stage transverse split

- **Schemes with relatively large numbers of bunch splittings possible**
  - D. Summers – “Potato slicer”
  - 16 → 1
- **Could be done at higher energy ?**
  - Overlap with LEMMA bunch combining ideas
- **More generally**
  - LEMMA phase space manipulations may also be useful for p-based source

Summary

- **Final Cooling:**
  - MAP Baseline system
    - Needs significant effort
    - Simulation, optics, B, rf
  - Other systems should be developed
  - Can be improved
- **Alternatives for improvements should be explored**
  - Inventions possible (X FTE)

Will be important research topic for IMCC